# TREE-RING STUDY OF HYDROLOGIC VARIABILITY IN THE PEACE-ATHABASCA DELTA, CANADA

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# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# LIST OF APPENDICES

# 1 Introduction

This report summarizes a tree-ring study of hydrologic variation in the Peace-Athabasca Delta. The study began with field collections of tree ring samples from the delta in late July, 2001. Ring widths and stable isotopes of carbon and oxygen in wood cellulose of rings were analyzed for hydrologic information. The initial objective was reconstruction of interannual variations in Lake Athabasca water level for the past 200 years. The study was later expanded to incorporate a larger network of existing tree-ring chronologies from western Canada and include reconstruction of streamflow of the Peace and Athabasca Rivers.

Tree rings of white spruce (*Picea glauca*) have previously been used to reconstruct annual variations in Lake Athabasca water level back to the early 1800s (Stockton and Fritts 1973). This study includes an updated reconstruction of Lake Athabasca water level, and extends the earlier tree-ring work in several ways: 1) improved tree-ring site coverage of the delta with additional chronologies, 2) increased sample depth at existing tree-ring chronologies, 3) analysis of the statistical relationship between tree-ring indices and climatic, 4) analysis of stable-isotope variations in cellulose of tree rings, 5) placement of the delta chronologies in the context of tree-ring variations over a much larger region of western Canada, 6) reconstruction of annual streamflow of the Peace and Athabasca Rivers, and 7) statistical testing of differences in tree-ring data and reconstructed water-level before and after construction of W.A.C. Bennett Dam.
Key data used in the study are listed in a series of appendices.

# 2 Hydrologic Setting

The Peace-Athabasca Delta, one of the world's largest inland deltas, is located in northeastern Alberta Province, Canada (Figure 1). Inflow to the 6,200 $km^2$ delta comes from several rivers, the largest of which is the Athabasca River. The Athabasca River, with a total drainage area of approximately 155,000 $km^2$ and a mean annual discharge of 431 $m^3$/sec at Athabasca, rises in the Rocky Mountains of Jasper National Park and flows northeastward across Alberta to the delta and Lake Athabasca. The Athabasca River is characteristic of rivers with substantial contribution from snowmelt in that flows are generally low in winter and high in spring and summer. Other rivers flowing into the delta have much more evenly distributed monthly mean flows, less dominated by melting snowpack. The delta also receives input from local precipitation, which averages 394 mm a year at Ft. Chipewyan.

Outflow from the delta is to the Peace River to the north through a series of channels over nearly flat terrain (Figure 2). The magnitude and even the direction of flow in these channels depends on the relative water levels of the Peace River and the open water bodies of the delta. Usually water flows through the delta's channels to the Peace River, but occasionally flow in the channels reverses depending on water level differences between the Peace River and the delta. Even when the Peace River is not contributing water to the delta, the outflow rate from the delta to the Peace River can be controlled by water-level difference in the two water bodies.

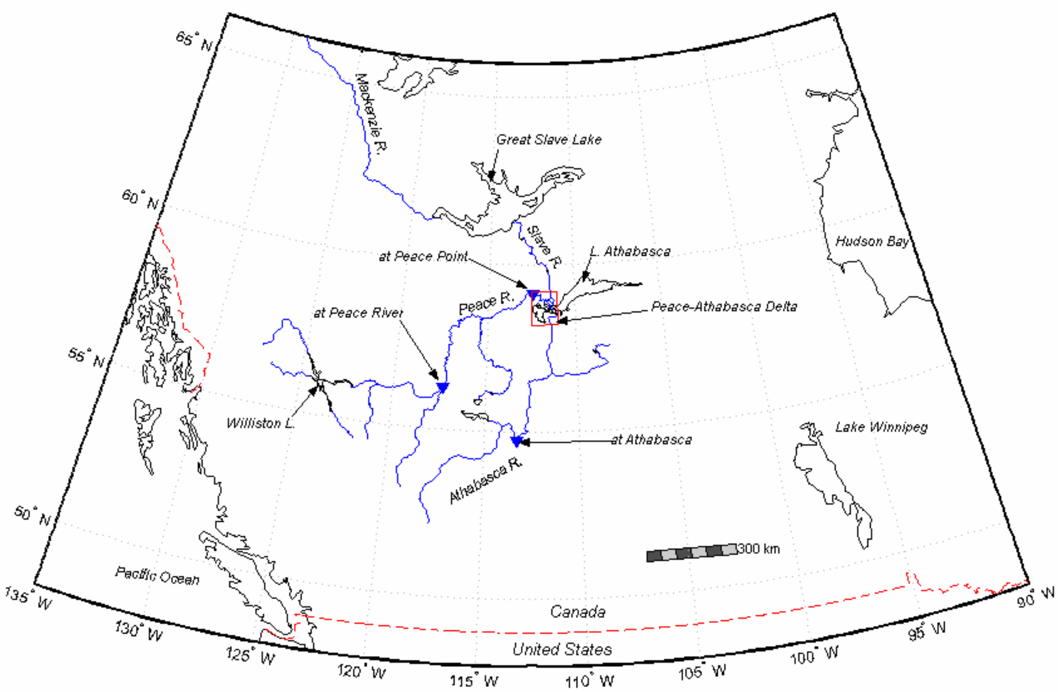


**Figure 1. Map of western Canada showing locations of Peace-Athabasca Delta, Peace River and Athabasca River. Stream gages used in the study are marked by triangles.**

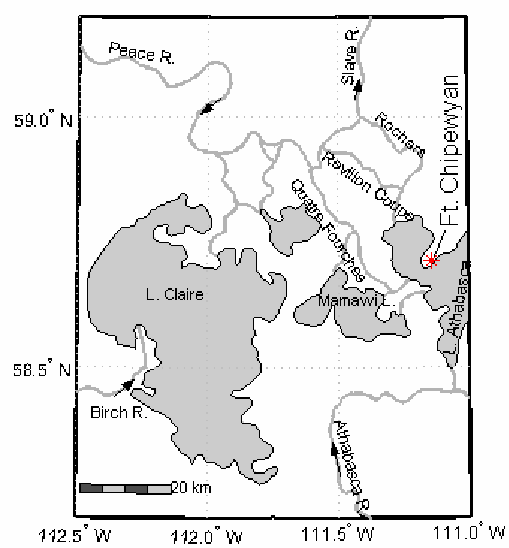


**Figure 2. Map showing rivers, channels and lakes in Peace-Athabasca Delta.**

The Peace River, with a total drainage area of approximately 300,000 $km^2$ and a mean annual flow of 1826 $m^3$/sec measured 560 km upstream of the delta at the town of Peace River, originates in the cold mountain streams of the Rockies of British Columbia. Downstream of the delta, the Peace River becomes the Slave River and flows northward to Great Slave Lake. Outflow from Great Slave Lake continues northward as part of the Mackenzie River system and eventually empties into the BeauFort Sea.

The natural flow of the Peace River was altered with the building of the W.A.C. Bennett Dam in British Columbia in the 1960's (Figure 1). Closure of the dam's gates in 1967 and subsequent filling of the reservoir in the period 1968-72 resulted in the storage of some 41 trillion litres of water in Williston Lake. A major change associated with regulation by the dam has been the evening out of the seasonal flows of the Peace River: mean monthly flows in the high-flow months (~May-Aug) are noticeably lower than before construction, while mean monthly flows in the low-flow months are higher than before construction.

The environmental characteristics of the Peace-Athabasca Delta are linked to the complex pattern of flows through the water channels (Figure 2). When the water level in Lake Athabasca is higher than in Claire and Mamawi Lakes, water flows westward into the delta. When Lake Athabasca is low, water flows eastward out of the delta lakes and into Lake Athabasca. The three main water channels in the delta are the Chenal des Quatre Fourches, Revillon Coupé and Rivière des Rochers – referred to in this report as the Quatre Fourches, the Coupe' and the Rochers. These channels are occasionally backflooded by periodic spring ice jam floods on the Peace River, resulting in replenishment of numerous perched basins throughout the delta (Timoney et al. 1997).

# 3 Data

Data used in the study include ring-width indices and stable isotope ratios of tree rings, as well as measurements of lake water level, precipitation, snowdepth, and air temperature.

## *3.1 Tree-Ring Data*

Several new chronologies were developed specifically for this study. These chronologies were augmented by archived tree-ring data collected as early as 1965.

**New tree-ring data.** Eight new white spruce (*Picea glauca*) tree-ring chronologies were developed in the delta from field collections in the summer of 2001. Approximate locations of the eight sites are shown on the map in Figure 3. Identifying information on the chronologies is included in Table 1 (first 8 sites). The chronologies are the predictors in the statistical model for reconstruction of Lake Athabasca water level and also are included in the predictor pool for the Peace River streamflow reconstruction. Samples from one of these sites (site 2, Quartre Fourches) were also analyzed for stable isotopes of carbon and oxygen. Details on the makeup and development of the new tree-ring data are found in the "Methods" and "Results" sections.

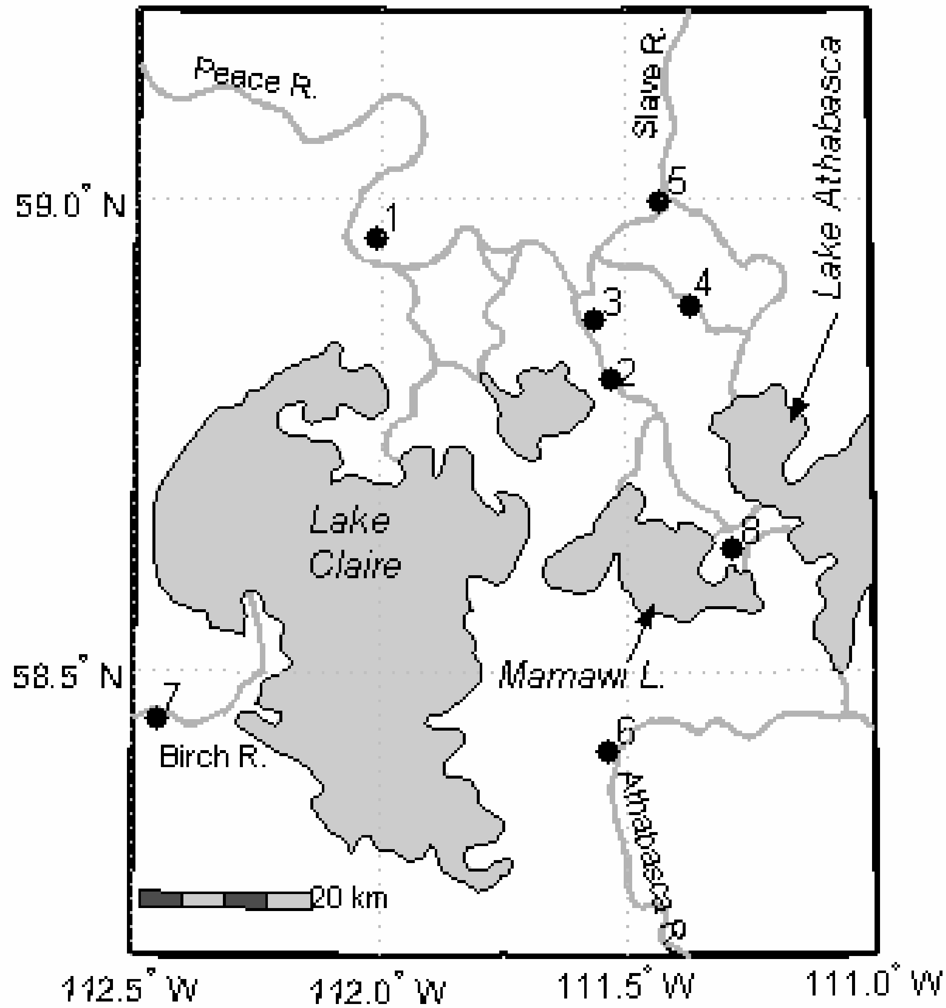


**Figure 3**. Map showing locations of tree-ring chronologies developed in the Peace-Athabasca Delta from 2001 field collections. These "delta" chronologies were formed by merging new collections with ring-width measurements collected in 1971. Sites are numbered as follows: 1) PPT=Point Providence, 2) QFS=Quatre Fourches, 3) HRS=Horseshoe Slough, 4) CPE=Revillon Coupe, 5) PRC=Peace-Rochers Confluence, 6) ATH=Athabasca River, 7) BIR=Birch River, 8) MAW=Mamawi Lake. See Table 1 for more information.

**Pre-existing tree-ring data.** Pre-existing data are defined here as ring-width chronologies and measurements other than those derived from the 2001 field collections. Two types of pre-existing data were used. First is a set of ring-width measurements of *P. glauca* from chronologies used in an earlier study of the delta (Stockton and Fritts 1973). Measurements from five of those delta sites were merged with the 2001 collections and re-standardized in producing the new chronologies. The ring widths of the Stockton and Fritts (1973) chronologies were downloaded from the International Tree-Ring data Bank (ITRDB). The names of the ITRDB ring-width computer files, chronology names as used in Stockton and Fritts (1973), and chronology site codes of the new chronologies (Table 1) are listed below:

cana100.rwl (Quatre Fourches) → QFS
cana102.rwl (Revillon Coupe) → CPE
cana103.rwl (Peace River I) → PRC
cana104.rwl (Peace River II) → PPT
cana105.rwl (Athabasca River) → ATH

Besides the Stockton and Fritts (1973) tree-ring chronologies, a set of pre-existing tree-ring chronologies from a broad swath of western Canada was used in the study. The network of chronologies was used to put the tree-ring variations of the delta in a larger spatial context. The network chronologies also served as predictors in reconstruction models for annual flows of the Peace and Athabasca Rivers. The network chronologies were obtained from the ITRDB by searching the ITRDB with an online search engine for all ring-width chronologies in the latitude/longitude box 48-66ºN, 90-135ºW. The wide geographical search range encompasses not only the runoff-producing area of the delta but a much broader are subject to the same large-scale climatological controls.

The ITRDB search identified 51 tree-rings chronologies, which were downloaded from the Web and then reduced to 45 chronologies by screening out duplicates. (Some ITRDB chronologies are merged chronologies, and both the merged and original versions are in the ITRDB.) An additional chronology not yet published or submitted to the ITRDB was contributed to this study by Glen MacDonald (personal communication).

The 8 new delta chronologies, 45 ITRDB chronologies, and additional contributed chronology form the 54-site tree-ring network for this study (Table 1, Figure 4).

### *3.2 Water Level, Streamflow, and Climatic Data*

Spreadsheets with daily water level, streamflow, and climatic data were supplied by B.C. Hydro (Jay Joyner, personal communication). The daily water-level data are measurements for Lake Athabasca at Ft. Chipewyan, Crackingstone Point and Goldfields. The conversion of these data to a homogeneous annual series of 10-day-mean water level at Ft. Chipewyan (required for the reconstruction model) is described under "Methods."

The streamflow data consist of daily discharge for 17 gages (10 on the Peace River, 7 on the Athabasca River). Primary emphasis was on two records: the Peace River at Peace

**Table 1**. Tree-ring chronologies used in study

| N[1] | File[2] | Name[3] | Species[4] | Location[5] Lat | Lon | Elev | Period[6] First | Last | Source[7] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | PPTWT1 | PPT, POINT PROVIDENCE | PCGL | 59.0 | -112.0 | 209 | 1698 | 2000 | Meko/Stockton |
| 2 | QFSWT1 | QFS, QUATRE FOURCHES | PCGL | 58.8 | -111.5 | 209 | 1712 | 2000 | Meko/Stockton |
| 3 | HRSWT1 | HRS, HORSESHOE SLOUGH | PCGL | 58.9 | -111.6 | 209 | 1801 | 2000 | Meko |
| 4 | CPEWT1 | CPE, REVILLON COUPE | PCGL | 58.9 | -111.4 | 209 | 1742 | 2000 | Meko/Stockton |
| 5 | PRCWT1 | PRC, PEACE/ROCHERS | PCGL | 59.0 | -111.4 | 209 | 1687 | 2000 | Meko/Stockton |
| 6 | ATHWT1 | ATH, ATHABASCA RIVER | PCGL | 58.4 | -111.5 | 209 | 1708 | 2000 | Meko/Stockton |
| 7 | BIRWT1 | BIR, BIRCH RIVER | PCGL | 58.5 | -112.5 | 209 | 1757 | 2000 | Meko |
| 8 | MAWWT1 | MAW, MAMAWI LAKE | PCGL | 58.6 | -111.3 | 209 | 1801 | 2000 | Meko |
| 9 | CANA008 | THELON GAME SANCTUAR | PCGL | 63.8 | -104.2 | 207 | 1574 | 1969 | Dennis |
| 10 | CANA155 | HORNBY CABIN | PCGL | 64.0 | -103.9 | 160 | 1491 | 1984 | Jacoby |
| 11 | CANA156 | MACKENZIE MOUNTAINS | PCGL | 65.0 | -127.8 | 1375 | 1626 | 1984 | Jacoby |
| 12 | CANA129 | WOOD BUFF SF | PCGL | 60.0 | -112.3 | 200 | 1833 | 1989 | Larsen |
| 13 | CANA130 | WOOD BUFF RL | PCGL | 59.8 | -112.2 | 250 | 1846 | 1989 | Larsen |
| 14 | CANA131 | WOOD BUFF BR | PCGL | 59.1 | -112.2 | 240 | 1866 | 1989 | Larsen |
| 15 | CANA132 | WOOD BUFF PR | PIBN | 59.8 | -112.2 | 300 | 1852 | 1992 | Larsen |
| 16 | CANA133 | WOOD BUFF NL | PIBN | 59.6 | -111.3 | 220 | 1857 | 1992 | Larsen |
| 17 | CANA135 | TOWERS RIDGE | PIFL | 51.2 | -114.7 | 1250 | 1315 | 1992 | MacDonald |
| 18 | CANA012 | KAMLOOPS_PSME+FRASER | PSME | 50.8 | -120.6 | 822 | 1420 | 1965 | Fritts/Schulman |
| 19 | CANA015 | KAMLOOPS_PIPO | PIPO | 50.8 | -120.6 | 822 | 1590 | 1965 | Fritts |
| 20 | CANA020 | POWERHOUSE, ALBERTA | PSME | 51.2 | -115.5 | 1432 | 1410 | 1965 | Ferguson |
| 21 | CANA022 | EXSHAW+TUNNEL+BANFF, | PSME | 51.2 | -115.6 | 1310 | 1460 | 1965 | Ferguson |
| 22 | CANA026 | PYRAMID LAKE+PATRICI | PSME | 52.9 | -118.1 | 1128 | 1540 | 1965 | Ferguson |
| 23 | CANA147 | SICAMOUS CREEK, BRIT | PCEN | 50.8 | -119.9 | 1550 | 1665 | 1994 | Parish |
| 24 | CANA161 | ADAMS LAKE PCEN | PCEN | 51.0 | -119.1 | 1900 | 1710 | 1996 | Parish |
| 25 | CANA162 | ADAMS LAKE ABLA | ABLA | 51.0 | -119.1 | 1900 | 1773 | 1996 | Parish |
| 26 | CANA174 | MOUNT CAIN | ABAM | 50.2 | -126.3 | 1005 | 1420 | 1999 | Parish |
| 27 | CANA038 | BRUNO LAKE, MANITOBA | PCGL | 51.6 | -95.8 | 1000 | 1822 | 1988 | Schweingruber |
| 28 | CANA039 | GUNISAO LAKE | PCMA | 53.5 | -96.4 | 860 | 1819 | 1988 | Schweingruber |
| 29 | CANA044 | WILLOW LAKE | PCMA | 62.2 | -119.1 | 620 | 1850 | 1988 | Schweingruber |
| 30 | CANA047 | FORT PROVIDENCE | PCGL | 61.2 | -117.4 | 500 | 1829 | 1988 | Schweingruber |
| 31 | CANA048 | FORT SIMPSON MCKENZI | PCGL | 61.7 | -120.7 | 375 | 1821 | 1988 | Schweingruber |
| 32 | CANA052 | BRAS D'OR LAKE (INSE | PCGL | 62.5 | -116.1 | 700 | 1759 | 1988 | Schweingruber |
| 33 | CANA053 | PETHAI PENINSULA | PCGL | 62.7 | -111.0 | 1400 | 1610 | 1988 | Schweingruber |
| 34 | CANA057 | FORT SIMPSON MCKENZI | PCGL | 61.7 | -120.7 | 375 | 1807 | 1988 | Schweingruber |
| 35 | CANA058 | AUSTIN LAKE | PCGL | 62.2 | -110.1 | 850 | 1818 | 1988 | Schweingruber |
| 36 | CANA070 | CHARLIE LAKE | PCMA | 60.0 | -100.4 | 1055 | 1768 | 1988 | Schweingruber |
| 37 | CANA074 | BUFFALO LAKE | PCGL | 60.3 | -115.3 | 803 | 1842 | 1988 | Schweingruber |
| 38 | CANA085 | CASSIAR | PCGL | 59.1 | -129.9 | 900 | 1817 | 1983 | Schweingruber |
| 39 | CANA086 | GNAT PASS, DEASE LAK | PCGL | 58.3 | -129.9 | 1200 | 1757 | 1983 | Schweingruber |
| 40 | CANA087 | WATSON LAKE | PCGL | 60.1 | -128.8 | 750 | 1742 | 1983 | Schweingruber |
| 41 | CANA088 | SUMMIT LAKE PASS | PCGL | 58.7 | -124.7 | 1260 | 1770 | 1983 | Schweingruber |
| 42 | CANA089 | FORT NELSON | PCGL | 58.3 | -122.8 | 690 | 1817 | 1983 | Schweingruber |
| 43 | CANA091 | SMITHERS SKI AREA | PCGL | 54.9 | -127.3 | 1200 | 1680 | 1983 | Schweingruber |
| 44 | CANA092 | PINE PASS | PCGL | 55.5 | -122.7 | 780 | 1697 | 1983 | Schweingruber |
| 45 | CANA093 | BEAR LAKE | PSME | 54.5 | -122.5 | 690 | 1773 | 1983 | Schweingruber |
| 46 | CANA094 | BELL MOUNTAIN | PCEN | 53.3 | -120.7 | 1530 | 1652 | 1983 | Schweingruber |
| 47 | CANA095 | SPRING LAKE | PSME | 51.9 | -121.3 | 810 | 1669 | 1983 | Schweingruber |
| 48 | CANA096 | SUNWAPTA PASS | PCEN | 52.3 | -117.0 | 2000 | 1608 | 1983 | Schweingruber |
| 49 | CANA097 | PEYTO LAKE | PCEN | 51.8 | -116.2 | 2050 | 1634 | 1983 | Schweingruber |
| 50 | CANA098 | VERMILION PASS | PCEN | 51.2 | -116.2 | 1500 | 1686 | 1983 | Schweingruber |
| 51 | CANA099 | SARRAIL GLACIER | PCEN | 50.6 | -115.2 | 2290 | 1499 | 1991 | Smith |
| 52 | CANA120 | KATHERINE CREEK N.W | PCGL | 65.0 | -127.5 | 680 | 1700 | 1989 | Szeicz |
| 53 | CANA124 | SKIPPING BULLET N.W | PCGL | 65.0 | -127.6 | 950 | 1780 | 1989 | Szeicz |
| 54 | WPPSTD | WHIRLPOOL POINT | PIFL | 52.0 | -116.5 | 1373 | 890 | 1996 | MacDonald |

(continued on next page)

Table 1. Tree-ring chronologies used in study (continued)

[1]Sequence number of chronology
[2]Computer file from which chronology extracted; sources as follows:
 Series 1-8, collection from summer 2001
 Series 9-53, International Tree-Ring Data Bank (ITRDB)
 Series 54, Glen MacDonald and Rosalyn Case, contribution of unpublished data
[3]Chronology name, sometimes shortened or modified to facilitate reference
[4]Species code (see Appendix 5)
[5]Latitude and longitude (decimal degrees) and elevation (meters above sea level)
[6]Year of coverage of the tree-ring standard chronology
[7]Collector: last name of primary individual responsible for chronology; "/" indicates chronology from merged collections at different times (e.g., Meko 2001 merged with Stockton 1971)

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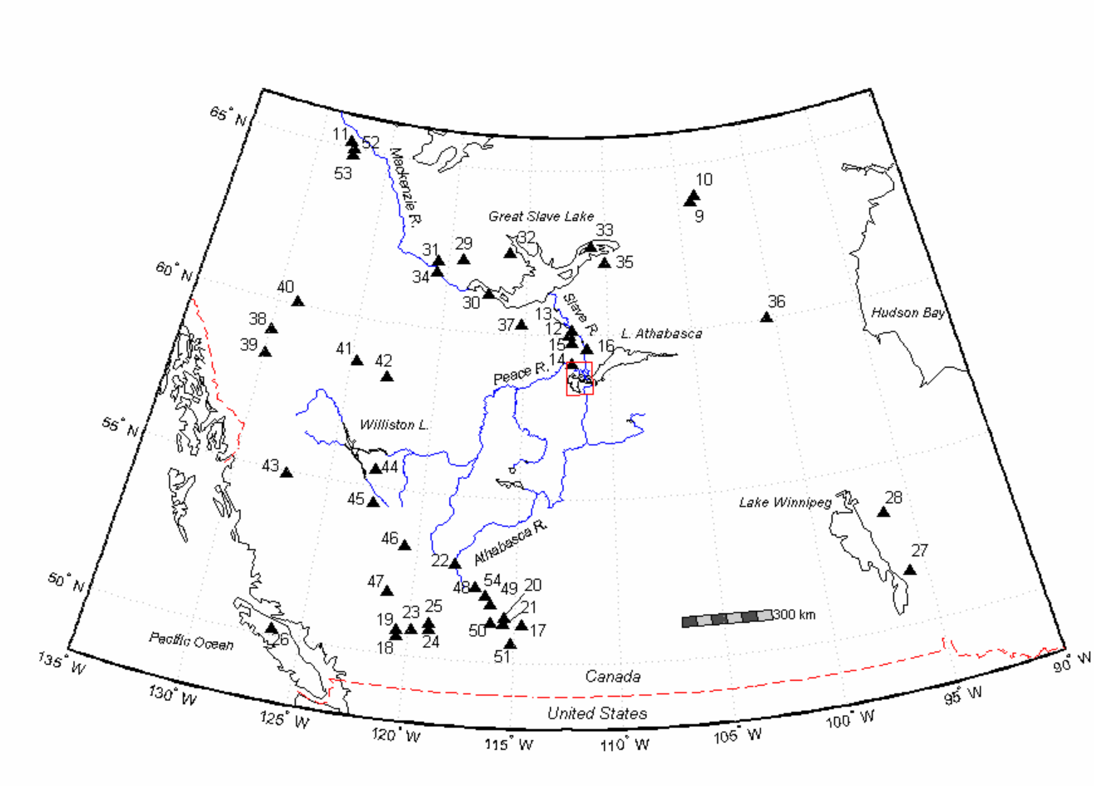



**Figure 4. Site locations of the 46 network chronologies outside the Peace-Athabasca Delta. Sites numbered as in Table 1. Note the lowest number on the map is 9: sites 1-8 are the new chronologies from the Peace-Athabasca Delta (see Figure 3).**

River and the Athabasca River at Athabasca. The Peace River record at Peace Point was also used, but only to check its strength of relationship with data from the gage upstream at Peace River. Locations of the gages used are marked on the map in Figure 1. The daily streamflow data for these gages begin as early as 1913 on the Athabasca River and 1915 on the Peace River, but have gaps from the 1930s to 1950s that severely shorten the available time series.

The climatic data used consist of daily measurements of total precipitation, snowdepth, and average daily temperature for the period 1967-98 at Ft. Chipewyan (58˚ 46'N, 111˚ 06'W, 232 m).

# 4 Methods

## 4.1 Field Collection Of Tree-Ring Samples

Increment core tree-ring samples (Stokes and Smiley 1968) of white spruce (*Picea glauca*) were collected from 13 sites between July 31 and August 8, 2001. A total of 137 white spruce were cored. At least two core samples were taken from each tree if possible. Most samples are from alluvial formations along the natural levees of river channels or from sloughs and perched basins offset from the channels. Five of the 13 sites, including 21 of the sampled spruce, are from bedrock islands later deemed too subject to human influence for hydrologic interpretation of the ring widths. The remaining 8 sites, with a total of 106 white spruce, comprise the main data set referred to as the "delta" tree-ring samples in this report.

Access to the sampling locations was either by helicopter or by motorboat. Trees were grouped into eight distinct "sites" according to clustering of trees within a radius of about ½ mile near an acceptable landing site of the helicopter, or along a stretch of channel accessed by motorboat (Figure 5). Site coordinates are listed in Table 1. Sites QFS and CPE are linear collections from boat trips down the Quatre Fourches and Revillon Coupe channels. Three sampled trees south of the weir on the River Rochers were also included in the linear collection at CPE (arrow in Figure 5). Only one of the 8 main sites is on a bedrock outcrop: site 8 (MAW) is a bedrock island at the edge of Mamawi Lake.

Open circles in Figure 5 mark the miscellaneous core samples taken from bedrock islands: English Island, Potato Island, Mouse Island and two unnamed islands. Ring widths from these sites frequently had large growth suppressions and surges in growth -- especially in the late 1800s -- that may have been related to logging or other anthropogenic influence.

Notes taken during field sampling included GPS readings at selected tree groups, tree location (distance and direction) relative to previous tree sampled, tree diameter as measured by steel tape, and location of tree relative to important hydrologic features or clearings. After removal from the tree, core samples were stored in paper straws and labeled with a code of tree/site/core.

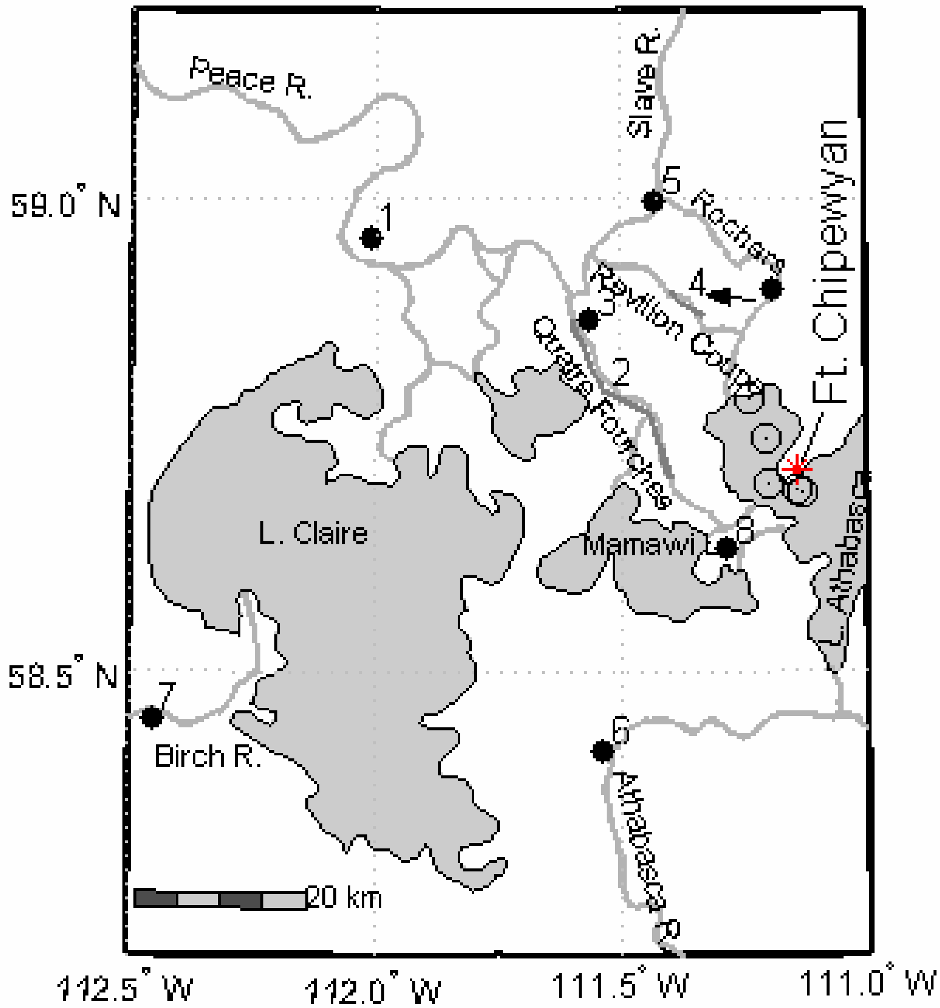



**Figure 5**. Map showing tree-ring sites collected in July and August, 2001. Sites are numbered as follows: 1) PPT=Point Providence, 2) QFS=Quatre Fourches, 3) HRS=Horseshoe Slough, 4) CPE=Revillon Coupe, 5) PRC=Peace-Rochers Confluence, 6) ATH=Athabasca River, 7) BIR=Birch River, 8) MAW=Mamawi Lake.

### 4.2 Tree-Ring Sample Preparation And Chronology Development

Core samples were allowed to air dry in the straws for two weeks, and were then glued into grooved wooden core mounts. Samples were then sanded with successively finer grades of sandpaper until ring boundaries became clear. These procedures are fairly standard in dendrochronology (Stokes and Smiley 1968).

The next step was to date the samples, or to assign an exact calendar year to each ring. Samples were dated by the skeleton-plotting, and rings were measured to the nearest 0.01 mm with a Bannister incremental measuring machine (Stokes and Smiley 1968). Dating and measurement was then computer-checked using computer software that summarizes the cross-correlation structure between pairs of high-pass filtered time series of ring-width measurements (Holmes 1983).

The dated and measured ring widths were then "standardized", or detrended and statistically combined into an index of annual growth variations at a site. The basic steps are as follows;

1. Fit a trend line separately to each core ring-width series
2. Convert the ring-width series to a dimensionless "core index" by dividing each annual measurement by the corresponding value of the fitted trend line
3. Average core indices within trees (usually two cores per tree) to get "tree indices"
4. Average tree indices over trees at a site to get the site chronology

The site chronology resulting from the above steps is a single dimensionless time series with mean 1.0, in which values greater than 1.0 indicate above normal growth and below 1.0 indicate below normal growth. The index in a given year is approximately the decimal fraction of normal growth: an index of 0.50 is 50% of normal growth, an index of 1.20 is 120% of normal, and so forth.

The key operation in standardizing tree-ring series for a climatic study such as this one is the fitting and removal of the trend, or low frequency ring-width variation deemed indistinguishable from age trend – a nonclimatic dependence of mean ring width on the age or size of tree (Fritts 1976). Because of biological and geometrical factors, ring-width generally changes gradually with tree age or size and would do so even if climate were invariable from year to year. For open-growth trees in semi-arid environments, the form of this age trend is often monotonic decreasing and frequently negative exponential (Fritts 1976).

For other site-types, the general form of the trend is impossible to specify, and may depend on changing competition for light and moisture due to changes in forest structure. Cook and Peters (1981) recommend the cubic smoothing spline as a reasonable data-adaptive detrending curve for such ring-width series. The cubic smoothing spline has the convenient property that the frequency response can be specified by a single spline parameter *n* (Cook and Peters 1981). The "*n*-year" spline is defined by Cook and Peters

(1981) as the cubic smoothing spline for which the amplitude of frequency response is 0.5 at a wavelength of *n* years. From time series theory on trend identification (Granger 1966), Cook and Peters (1981) suggest that the appropriate choice of *n* depends on the length of the individual ring-width series, and that a reasonable choice is some large fraction (e.g., 70%) of the series length. Series length usually varies considerably from tree-to-tree. To maintain uniformity in trend removal within sites, chronologies for this study were detrended with *n*-year cubic smoothing splines with *n* equal to the median sample length of ring-width series at the site.

### *4.3 Stable-Isotope Analysis*

Wood samples for stable istotope analysis were taken by separating individual groups of dated rings from cores with a surgical scalpel. The wood cellulose was analyzed for stable isotope ratios of carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$).

Samples for groups of 2-4 consecutive rings were ground and extracted first with toluene and ethanol and then with toluene alone. Samples were then delignified to holocellulose in an acidified sodium-chlorite solution (Leavitt and Danzer 1993). Holocellulose was combusted to $CO_2$ for carbon-isotope analysis or pyrolized to CO for oxygen-isotope analysis on a Finnigan Delta P155 mass spectrometer. The resulting isotope ratios returned from the laboratory are expressed in units of per mil (‰) :

$$\delta^{13}C\left({}^{o}/_{oo}\right)=\left(\frac{\left({}^{13}C/{}^{12}C\right)_{sample}}{\left({}^{13}C/{}^{12}C\right)_{standard}}-1\right)1000 \qquad (1)$$

where $\left({}^{13}C/{}^{12}C\right)_{standard}$ is the international PDB standard (Craig 1957; Coplen 1996), or

$$\delta^{18}O\left({}^{o}/_{oo}\right)=\left(\frac{\left({}^{18}O/{}^{16}O\right)_{sample}}{\left({}^{18}O/{}^{16}O\right)_{standard}}-1\right)1000 \qquad (2)$$

where $\left({}^{18}O/{}^{16}O\right)_{standard}$ is standard mean ocean water, SMOW (Coplen 1995).

### *4.4 Reduction Of Hydrologic And Climatic Data*

**Water level of Lake Athabasca.** Stockton and Fritts (1973) used the July 11-20 mean water level as their primary seasonal grouping for analysis with tree rings. It was desirable for the seasonal window to be later than any expected short-term disruption from spring ice-jam floods, and to be representative of the mid-summer period when water levels usually reach high levels in response to sustained annual runoff from winter snowmelt in the upper reaches of the main rivers. After exploratory analysis of various alternative windows – correlating the seasonal water level with tree-ring series -- I selected July 11-20 period as a being adequately representative of summer water levels for purposes of tree-ring reconstucton.

A time series of July 11-20 mean water level for Ft. Chipewyan was generated from the daily water-level measurements at Ft. Chipewyan supplemented when necessary by daily measurements at Crackingstone Point and Goldfields. The records were merged with the aim of minimal distortion due to differences in mean water level at the three locations. In order of decreasing priority, the daily water-level data used for the final Ft. Chipewyan series were:

1) As measured at Ft. Chipewyan

2) As measured at Crackingstone Point, shifted an amount equal to the mean daily difference in water levels at Crackingstone Point and Ft. Chipewyan. The size of the shift was based on mean observed daily differences. Focus was on the summer, so that the adjustment procedure was restricted to the period May 21-Sept 30, or Julian days 142-274. The mean difference in water level between the two locations for each day of that day-window was plotted, and then smoothed using a cubic spline to remove day-to-day irregularities (Figure 6, top). The smoothed curve yielded a shift amount for each day. On average for Julian days 142-274 the shift is -.05 m (water level usually higher at Crackingstone Point than at Ft. Chipewyan).

3) As measured at Goldfields, shifted an amount equal to the mean daily difference in water levels at Goldfields and Ft. Chipewyan. The same procedure as for Crackingstone Point yielded a spline curve for transferring Goldfield measurements to Ft. Chipewyan (Figure 6, bottom). Water levels were on the average (for the 142-274 window) about 2.25 m higher at Goldfields than at Ft Chipewyan.

For some years in the period 1934-2000, the above procedure still left incomplete data for some days in the July 11-20 window as no daily data were available at Ft. Chipewyan and none available for shifting at the other two gages. For those years with fewer than 10 days of data in the 10-day window, a 10-day mean was approximated by the $n$-day mean, where $n<10$. Three years (1945, 1946, 1954) had no data in the July 11-20 window at any of the three gage locations. For those years values of estimated data were taken from Stockton and Fritts (1973, Table 1).

The resulting annual time series of July 11-20 mean lake-level variations at Ft. Chipewyan is plotted along with a listing of the data values in Figure 7. As quality control, the series was plotted on the same axes as the July 11-20 mean water level listed in Stockton and Fritts (1973) (not shown). The superposed series were so similar as to be indistinguishable in the plots for most years. A discrepancy in 1950 was checked against original data in Bennett (1970) and appears to be an error in Stockton and Fritts (1973). The value of 209.28m for July 11-20, 1950, as computed from data in Bennett (1970) was used. Other differences in the two plotted series are probably due to slightly different ways of incorporating the Goldfields and Crackingstone Point data as estimates, and regardless are likely too small to be of consequence to our analysis.

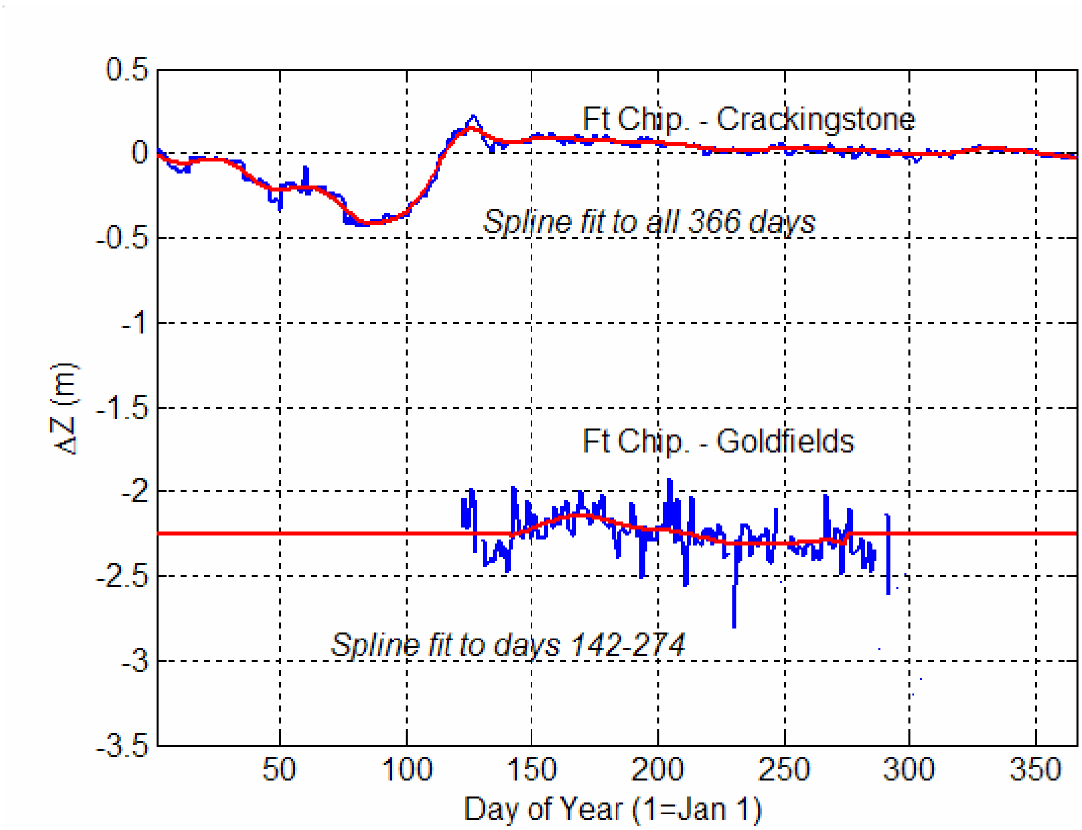
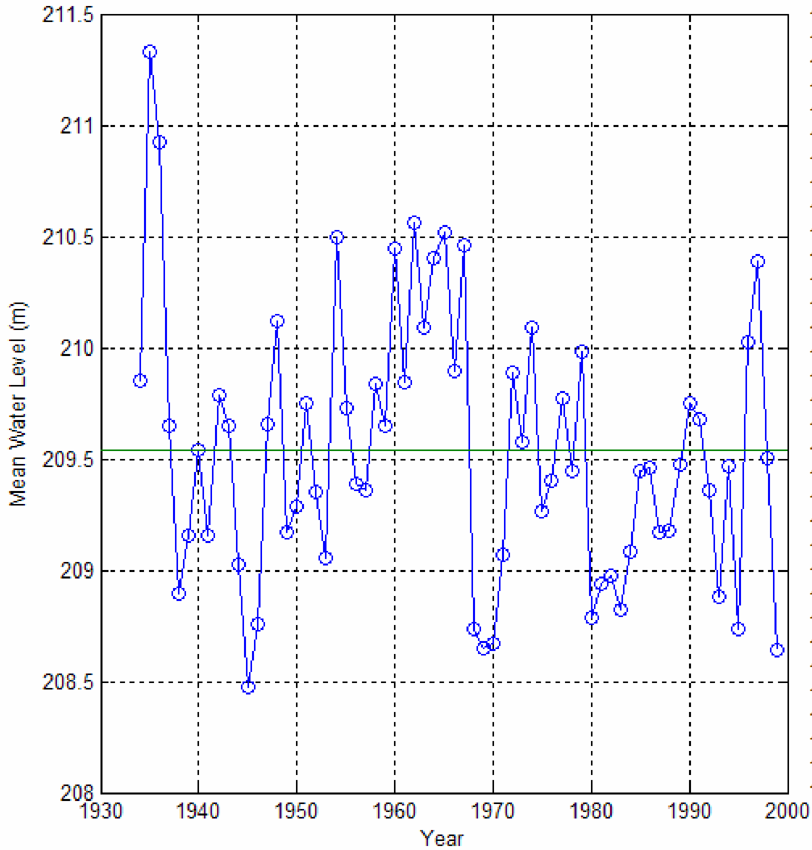



**Figure 6.** Graph illustrating water-level adjustment from other gages to Ft. Chipewyan. Gages are Ft. Chipewyan, Crackingstone Point, and Goldfields. Objective is complete record for Ft. Chipewyan. Irregular line is mean daily difference in water level for specific Julian days based on only those years with simultaneous (same day) data at Ft. Chipewyan and the other gage. Smooth curves is cubic smoothing spline fit to the difference. Shift represented by spline curve was used to adjust daily values for Crackingstone Point or Goldfields when those values were used as estimates for missing data at Ft. Chipewyan.




| | | | |
|---|---|---|---|
| 1934 | 209.85 | 1967 | 210.46 |
| 1935 | 211.33 | 1968 | 208.73 |
| 1936 | 210.92 | 1969 | 208.65 |
| 1937 | 209.65 | 1970 | 208.67 |
| 1938 | 208.90 | 1971 | 209.07 |
| 1939 | 209.16 | 1972 | 209.88 |
| 1940 | 209.54 | 1973 | 209.58 |
| 1941 | 209.16 | 1974 | 210.09 |
| 1942 | 209.79 | 1975 | 209.26 |
| 1943 | 209.65 | 1976 | 209.40 |
| 1944 | 209.03 | 1977 | 209.78 |
| 1945 | 208.47 | 1978 | 209.44 |
| 1946 | 208.75 | 1979 | 209.98 |
| 1947 | 209.65 | 1980 | 208.79 |
| 1948 | 210.12 | 1981 | 208.94 |
| 1949 | 209.17 | 1982 | 208.97 |
| 1950 | 209.29 | 1983 | 208.82 |
| 1951 | 209.75 | 1984 | 209.08 |
| 1952 | 209.35 | 1985 | 209.44 |
| 1953 | 209.05 | 1986 | 209.46 |
| 1954 | 210.49 | 1987 | 209.17 |
| 1955 | 209.73 | 1988 | 209.18 |
| 1956 | 209.39 | 1989 | 209.48 |
| 1957 | 209.36 | 1990 | 209.75 |
| 1958 | 209.84 | 1991 | 209.68 |
| 1959 | 209.65 | 1992 | 209.36 |
| 1960 | 210.45 | 1993 | 208.88 |
| 1961 | 209.84 | 1994 | 209.47 |
| 1962 | 210.56 | 1995 | 208.74 |
| 1963 | 210.09 | 1996 | 210.02 |
| 1964 | 210.40 | 1997 | 210.39 |
| 1965 | 210.52 | 1998 | 209.50 |
| 1966 | 209.89 | 1999 | 208.64 |

**Figure 7.** Time series plot of 10-day-mean water level of Lake Athabasca at Ft. Chipewyan for period July 11-20. Series derived from measurements and estimates as described in text**.**

The observed water level series clearly shows substantial low-frequency variance, manifested by increasing water level from the 1940s to mid-1960s, followed by an irregular decline into the 1980s. Multi-year periods of marked low water level are 1944-45, 1968-70 and 1980-83. The most striking period of high water level is 1960-67.

**Streamflow and climatic data.** Daily streamflow for the Peace and Athabasca Rivers and climatic series for Ft. Chipewyan were aggregated into seasonal series either by taking the arithmetic sum or mean over the interval of interest. Observed data only were used in seasonalizing, so that if one or more days in the season had missing data, the annual value was marked as missing for that year.

### *4.5 Statistics*

**Significance of correlation.** Strength of linear association between pairs of variables was measured by the product-moment, or Pearson, correlation coefficient (Benjamin and Cornell 1970; Wilks 1995).

Significance of correlation between two variables was tested with a *t*-test (Benjamin and Cornell 1970, p. 417). The null hypothesis for the test is that the population correlation coefficient is zero, and the alternative hypothesis is that the population coefficient is not zero. The test statistic is given by

$$T = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \tag{3}$$

where $r$ is the sample correlation coefficient and $n$ is the sample size, or number of pairs of observations. If the series are jointly normally distributed and the population correlation coefficient is zero (no correlation), $T$ follows a $t$ distribution with $n-2$ degrees of freedom. The test statistic $T$ is compared with critical points of the $t$ distribution to judge statistical significance of the sample correlation coefficient. The critical point for a given $\alpha-$level is read from a table for the $t$ distribution as $c = t_{\alpha/2,n-2}$ and the null hypothesis is rejected if $T$ falls outside the range $-c \le t \le +c$. A two-tailed test, with alternative hypothesis that the population coefficient is not zero, was used in all analyses in this report.

Autocorrelation adjustment. If the time series being correlated are themselves autocorrelated, the number of independent samples is fewer than the number of years of data and the significance of a given correlation coefficient is lower than indicated by the above procedures. In this case the sample size can be adjusted to an effective sample size as recommended by Dawdy and Matalas (1964):

$$n' = n\frac{\left(1-r_{1,x}r_{1,y}\right)}{\left(1+r_{1,x}r_{1,y}\right)} \tag{4}$$

where $r_{1,x}$ and $r_{1,y}$ are the first-order sample autocorrelation coefficients of the two time series (Wilks 1995), and *n'* is an "effective" sample size that can be used in place of *n* in (3).

Bonferroni adjustment. In evaluating significance of multiple correlations, an additional adjustment called the "Bonferroni adjustment" was applied (Snedecor and Cochran 1989, p. 116, 167). If a test is repeated several times and each time a sample correlation is computed and tested for significance at the 0.05 $\alpha$-level, the probability of getting at least one "significant" correlation is actually greater than 0.05. The confidence should be widened to account for the increased probability. The algorithm for the Bonferroni adjustment can be derived from the binomial distribution, which gives the probability of a least one success in $k$ trials given the probability of success in a single trial. For evaluation of significance of correlation coefficients, if the number of correlations tested is $k$, the desired $\alpha$-level should be divided by $k$ to get the adjusted $\alpha$-level. For example, for $k = 10$ evaluated correlations and a desired 95% confidence level ($\alpha = 0.025$ for 2-tailed test), the $\alpha$-level for the Bonferroni-adjusted confidence interval is $\alpha' = \alpha/k = 0.025/10 = 0.0025$. Lowering the $\alpha$-level widens the confidence interval, making it less likely to conclude that the correlation is significantly different from zero. The appropriate hypothesis for using the Bonferroni adjustment is the "universal null hypothesis", which for the correlation example is that all evaluated correlations are zero. Both the Bonferroni adjustment and the autocorrelation adjustment were used in correlation analyses in this report when appropriate.

**Expressed population signal (EPS).** The EPS statistic estimates the ability of a mean-value series based on a limited number of sample time series to approximate the unknown population time series signal (Wigley et al. 1984). The EPS statistic is based on the theory of correlated variables, and reflects the need for a larger number of sample series to capture a population signal as the mean between-series correlation becomes smaller. In the tree-ring context, the EPS statistic is used to measure how adequately a tree-ring chronology based on $n$ trees approximates the unknown tree-growth signal hypothetically achievable from a sample of infinite size. The EPS statistic is given by

$$\mathrm{EPS}(n) = \frac{n\overline{r}_{bt}}{n\overline{r}_{bt} + (1 - \overline{r}_{bt})} \qquad (5)$$

where $n$ is the number of trees averaged, and $\overline{r}_{bt}$ is the mean between-tree correlation of the tree-ring indices for various trees at a site.

Wigley et al. (1984) suggest an EPS of 0.85 as a rough guideline for whether the sample size is sufficiently large at a site. In this study, the EPS statistic was used as a guide for identifying the period of adequate replication of tree-ring chronologies.

**Sample-size-weighted mean tree-ring chronology**. Various methods are available for summarizing the time series variations of a group of tree-ring chronologies as a single time series. In this study a sample-size-weighted mean of available chronologies was used as a summary time series. The summary series is referred to as the "delta-mean" tree-ring series in this report. The algorithm for the delta mean series is presented here as the method is not to my knowledge published elsewhere. The idea is simple: in each year of the tree-ring record, the mean series is a weighted mean over all available chronologies in that year, and the weights on a chronology are proportional to the number of trees in the chronology.  The advantage over the arithmetic mean is that chronologies are discounted as their sample size decreases.  The algorithm automatically guards against distortion of the mean series due to differences in means and standard deviations of the individual chronologies.

The steps in computation are are as follows:

*Convert each chronology to a time series of standardized anomalies*

$$u_{i,t} = \frac{\left(x_{i,t} - \overline{x}_i\right)}{s_i} \tag{6}$$

where $u_{i,t}$ is the standardized anomaly chronology for site $i$ in year $t$, $x_{i,t}$ is the original chronology value in that year, $\overline{x}_i$ is the mean of the chronology computed on all available years, and $s_i$ is the standard deviation of the chronology computed on all available years.

*Weight the standardized anomalies by the sample size in any given year*

$$\overline{u}_t = \sum_{i \in I} w_{i,t} u_{i,t} \tag{7}$$

where $\overline{u}_t$ is the weighted standardized anomaly of tree-ring index in year $t$, $I$ is the set of chronologies available in year $t$, and $w_{i,t}$ are weights proportional to the number of trees at site $i$ in that year, scaled such that $\sum_{i \in I} w_{i,t} = 1$.

*Re-scale the weighted series to original units using the global mean and standard deviation*

$$u_t^* = \overline{x} + \overline{s}\,\overline{u}_t \tag{8}$$

where

$$\overline{x} = \frac{\sum_{i=1}^{N} \overline{x}_i}{N} \tag{9}$$

and

$$\overline{s} = \frac{\sum_{i=1}^{N} \overline{s}_i}{N} \tag{10}$$

are the arithmetic means of the individual series means and standard deviations, and $N$ is the total number of series available for the analysis.

**Principal components analysis.** Principal components analysis (PCA), as described by Mardia et al (1979) was used to identify linear combinations of tree-ring chronologies accounting for most of the variance in multivariate tree-ring data sets. The principal components, or PCs, resulting from a PCA are linear combinations of the original variables with the properties that 1) each PC is orthogonal to all other PCs, and 2) PC#1 accounts for the most variance in the data, PC#2 accounts for the second most, etc., and 3) all PCs combined account for the total variance of the data.

The PC scores, the time series of the linear combinations of the original variables, are essentially transformations of the original variables. PC scores of tree-ring chronologies were used in two ways in this study: 1) as simple summary series of tree-ring variation, and 2) as predictors in regression models to reconstruct lake water level and streamflow. All principal component analyses in this report were conducted on the correlation matrix rather than the covariance matrix of the original variables.

**Wilcoxon rank-sum Test.** This rank-sum test, also called the Mann-Whitney test (Conover 1981), is used to test the null hypothesis that the populations from which two samples are drawn are the same. The test was used in this study to test whether samples (e.g., reconstructed water levels) before and after Bennett Dam come from the same populations. In applying the test, the observations from the two samples are lumped together, sorted in order of magnitude, and assigned ranks from smallest to largest. The sums of the ranks of observations from each of the two samples is then computed, and a function of the smaller of those rank-sums is the test statistic. If one sample has most of the low values and the other most of the high values, the sample with the low values will obviously have a much lower rank sum. The test statistic is evaluated for significance by referring to probability levels of a normal distribution (Conover 1981).

**Regression.** Multiple linear regression (MLR) was selected as the statistical model for reconstruction. The MLR model is well suited for providing predictions with error bars and summary statistics from readily available software (Weisberg 1985), and has been widely used in dendroclimatic reconstruction (e.g., Stockton and Meko 1983; Blasing and Duvick 1984; Meko and Graybill 1995; Meko et al. 2001). The model expresses the value of a predictand variable as a linear function of one or more predictor variables and an error term:

$$\begin{aligned} y_i &= b_0 + b_1 x_{i,1} + b_2 x_{i,2} + \ldots + b_K x_{i,K} + e_i \\ x_{i,k} &= \text{value of } k^{\text{th}} \text{ predictor in year } i \\ b_0 &= \text{regression constant} \\ b_k &= \text{coefficient on the } k^{th} \text{ predictor} \\ K &= \text{total number of predictors} \\ y_i &= \text{predictand in year } i \\ e_i &= \text{error term} \end{aligned} \tag{11}$$

The model (11) is estimated by least squares, which yields parameter estimates such that the sum of squares of errors is minimized. The resulting prediction equation is

$$\hat{y}_i = \hat{b}_0 + \hat{b}_1 x_{i,1} + \hat{b}_2 x_{i,2} + \ldots + \hat{b}_K x_{i,K} \tag{12}$$

In this study, the $x_{i,k}$ are either tree-ring chronologies or PC scores of tree-ring chronologies and $y_i$ is annual streamflow or seasonal lake-level. Accuracy of regression models was evaluated by calibration statistics and by validation statistics derived from cross-validation (Michaelsen 1987). Calibration statistics used include $R^2$, $R^2_{adj}$, $F$-level of the regression equation, and the standard error of the estimate (Weisberg 1985).

Validation statistics used include the root-mean-square-error of cross-validation ($\mathrm{RMSE_v}$) and the reduction-of-error statistic (RE). $\mathrm{RMSE_v}$, a measure of the average size of the prediction error for the validation period, is computed as the square root of the mean squared error of validation:

$$\mathrm{RMSE}_v = \sqrt{\mathrm{MSE}_v} = \left[ \frac{\sum_{i=1}^{n_v} \left( \hat{e}_{(i)} \right)^2}{n_v} \right]^{1/2} \tag{13}$$

where $n_v$ is the number of years in the validation period, and $\hat{e}_{(i)}$ is the cross-validation error (observed minus predicted value of predictand) for observation $i$ based on a model calibrated on all years except $i$. $\mathrm{RMSE_v}$ is recommended by Weisberg (1985) as "sensible" estimate of the prediction error when the regression model is applied to data outside the calibration period -- as it is here for tree-ring reconstructions. An approximate 95% confidence interval for reconstructed values is $\pm 2\mathrm{RMSE_v}$. The reduction of error statistic, as computed in cross-validation, is given by

$$\mathrm{RE} = 1 - \frac{\mathrm{SSE}_v}{\mathrm{SSE}_{null}} \tag{14}$$

where $\mathrm{SSE_v}$ is the sum of squares of cross-validation errors and $\mathrm{SSE_{null}}$ is the sum of squares of error if the calibration period mean is used as the prediction for each year. Essentially, $\mathrm{RE} > 0$ indicates that the prediction has "some" skill relative to a prediction based on no knowledge (Gordon 1982).

The steps in developing regression models for this study are as follows:

1. A pool of potential predictor variables was assembled based on prior knowledge of the problem and correlation analysis between the variable to be reconstructed (predictand) and various tree-ring chronologies or PCs of tree-ring chronologies.

2. The predictors were entered into the regression model in a stepwise-forward method (Draper and Smith 1981), such that each new predictor resulted in the maximum possible reduction of residual variance.
3. After each step in the stepwise regression, the model was validated by "leave-one-out" cross-validation (Michaelsen 1987) to guard against overfitting the model (Wilks 1995; Meko 1997; Meko et al. 2001).
4. Entry of variables was terminated based on the stopping rule that additional predictors are beneficial only as long as $RMSE_v$ continues to decrease. Equivalently, the RE statistic must continue to increase. By this stopping rule, model accuracy is required to improve when the model is tested on <u>independent</u> data to justify increased model complexity.

At times the procedure had to be modified to accommodate irregularities of the data. For example if both a PC and one of the chronologies in the PC were indicated as useful predictors, the PCA was recomputed without the important single chronology and the regression analysis was repeated. This modification avoided the dilemma of having two predictors functionally related to one another in the regression model.

**Smoothing.** Guassian filters, as described by Mitchell et al. (1966) were used to smooth annual time series to emphasize low-frequency variations. The Guassian filter is a symmetric bell-shaped filter whose weights are all positive and sum to 1.0. The Gaussian filter is convenient for filtering time series in that the user can easily design the filter to emphasize frequency range of interest. The wavelength, $\lambda$, at which the amplitude of frequency response is 0.5 is the only parameter needed. In this report, Gaussian filters with $\lambda$=10, 25 and 50 years were used. The filter weights for these filters are listed in Appendix 6.

Running means were also used to summarize reconstructions. The running mean, also called the moving average, is just the arithmetic average over a specified successive number of values of the time series.

**Spectral analysis.** Spectral analysis was used to describe the distribution of variance of reconstructed time series as a function of frequency or wavelength. The method used is called the smoothed periodogram method, which is described by Bloomfield (2000). In this method, the raw periodogram of the time series is computed and then smoothed by a succession of filters or smoothing spans, called Daniell filters, to produce the spectral estimate. A confidence interval for the spectral estimates is based on a chi-square distribution, and the width of the confidence interval depends on settings for the smoothing spans as well as the time series length and other parameters of the analysis (Bloomfield 2000).

## 5 Results and Discussion

### 5.1 Chronology Development

The steps described under "Methods" were applied to develop the eight delta tree-ring chronologies at locations shown on the map in Figure 3 . Chronology information is summarized in Table 2. The chronologies all have an ending year of 2000, the last complete ring of growth in August, 2001. The start year ranges from 1687 at PRC to 1801 at HRS and MAW.

As indicated in Table 2, five of the delta chronologies are hybrids constructed by merging ring-width series from the 2001 field collections with ring-width measurements from Stockton and Fritts (1973). Both sets of ring-width series were standardized by the same methods using the same criteria for detrending splines. The $n$-values for splines used on the eight delta chronologies are listed in Table 2. Values of $n$ range from 118 yr at site MAW to 201 yr at site ATH. Approximately, these settings imply that any climatic variation at wavelength longer than 118 yr at MAW and 201 yr at ATH cannot be identified with these data, as the detrending operation has removed that low-frequency component of growth.

Because the tree-ring chronology is a mean-value function, the stability of the estimate of the chronology depends on the sample size, or number of trees, in any given year. If indices from different trees are highly correlated, fewer trees are needed to represent the site tree-ring variation than if indices are poorly correlated between trees. The mean between-tree correlation of indices ranges from 0.41 to 0.56 at the eight delta sites (Table 2). The corresponding EPS statistic (see "Methods") can be used to estimate the minimum acceptable number of trees for any given site chronology. This critical sample size and the year it is reached are listed under "$\text{Year}_c$" in Table 2.

The computed values of EPS indicate that between 5 and 9 trees are required at the delta tree-ring sites to adequately represent the population tree-ring signal. Maximum sample size at the delta sites ranges from 11 to 29 trees. The best-sampled site by the EPS criterion is ATH, where the critical EPS is reached in 1736. At the opposite extreme, site MAW does not reach adequate sample size until 1873. In general, the sample size for the delta chronologies becomes adequate by the early 1800s. If tree-ring indices are averaged over multiple site chronologies, the sample size deficiency at individual sites is less important, so that it should be reasonable to expect the set of delta chronologies as a whole to adequately capture the population tree-ring signal back to at least A.D. 1800

### 5.2 Internal Consistency Of Tree-Ring Variations On Delta

**Inter-site correlation.** For the period 1801-2000, the product-moment correlations between pairs of chronologies are all positive and significant at the $\alpha = 0.05$ level by a two-tailed test (Benjamin and Cornell 1970). The two most highly correlated chronologies $(r = 0.85)$ are the two sites along the Peace River (PPT and PRC). The least-correlated sites $(r = 0.33)$ are BIR and MAW. The relatively low correlation

**Table 2.** Summary statistics of Peace-Athabasca Delta tree-ring chronologies

| N[1] | CODE[2] | SITE NAME[3] | PERIOD[4] | SAMPLE SIZE[5] | $r_{bt}$[6] | $YEAR_c$[7] | FIT[8] |
|---|---|---|---|---|---|---|---|
| 1 | PPT, | POINT PROVIDENCE | 1698-2000 | 22(7) | 0.56 | 1788(5) | 152-yr |
| 2 | QFS, | QUATRE FOURCHES | 1712-2000 | 29(13) | 0.51 | 1771(6) | 138-yr |
| 3 | HRS, | HORSESHOE SLOUGH | 1801-2000 | 12 | 0.56 | 1817(5) | 155-yr |
| 4 | CPE, | REVILLON COUPE | 1742-2000 | 27(12) | 0.47 | 1825(7) | 127-yr |
| 5 | PRC, | PEACE/ROCHERS | 1687-2000 | 25(10) | 0.55 | 1803(5) | 162-yr |
| 6 | ATH, | ATHABASCA RIVER | 1708-2000 | 19(11) | 0.41 | 1736(9) | 201-yr |
| 7 | BIR, | BIRCH RIVER | 1757-2000 | 14 | 0.57 | 1805(5) | 129-yr |
| 8 | MAW, | MAMAWI LAKE | 1801-2000 | 11 | 0.46 | 1873(7) | 118-yr |

[1]Site number as used on map in Figure 4
[2]Three-character site code, used in labeling samples
[3]Name of site
[4]First and last years of measured ring widths at the site
[5]Maximum number of trees in any year of chronology (with number of trees coming from Stockton and Fritts (1973) collection in parentheses
[6]Mean between-tree correlation (see text)
[7]Critical year – year in which expressed population signal (EPS) reaches 0.85, with corresponding sample size, as number of trees, in parentheses
[8]Detrending-spline specification: wavelength at which spline used to detrend ring widths has 0.5 amplitude of frequency response (see text)

between BIR and MAW is perhaps due to both sites being more removed from the open-body lake level variations than other sites: BIR is along the Birch River west of Lake Claire and MAW is elevated tens of meters above the delta on a bedrock island southwest of Ft. Chipewyan. All eight tree-ring chronologies are highly autocorrelated, with the first-order autocorrelation coefficient ranging from 0.33 at site MAW to 0.77 at sites PRC and QFS. Between-site correlations remain significant if the sample size is adjusted as recommended by Dawdy and Matalas (1964) to account for non-zero first-order autocorrelation of the individual series.

**Principal components of delta tree-ring chronologies.** The high inter-site correlation suggests that the eight delta chronologies contain redundant information, and that the common signal might be more concisely expressed by combining chronologies. A principal components analysis (PCA) run on the correlation matrix of chronologies, 1801-2000, indicates that 62% of the tree-ring variance is accounted for by just one PC (Table 3). That PC has positive weights on all 8 sites, with highest weights toward the Peace River (north). The first PC is the only PC with an eigenvalue greater than 1, suggesting that this first PC might by itself summarize the important spatial coherence in the tree-ring data (Mardia et al. 1979). The second PC, with large negative weights on ATH and MAW and positive weights on CPE and PRC, hints at a northeast/southwest contrast in growth anomalies as a secondary or underlying spatial mode of variability.

**Summary series of common tree-ring variation.** The scores of PC#1 and the sample-size-weighted mean (see "Methods) are two alternative time series that summarize the common tree-ring variation over the delta. The two series are plotted in Figure 8. The PC score series is of course restricted to the period of data in common to all eight chronologies, while the delta-mean series extends back to the first year of the earliest series.

For the period of overlap, differences in the two versions of delta-mean tree-ring index are small. Both series emphasize the relatively large swings from high growth to low growth in the 20$^{th}$ century. In fact, the extremes of high and low index in the 20$^{th}$ century are greater than in the earlier record. Growth rate peaked in the mid-1930s and mid-1960s, and bottomed out in the mid-1940s and early 1980s. Earlier periods of extended low growth were centered near 1760 and 1890. Earlier periods of high growth occurred in the 1730s and 1850s. Variations before 1800 are increasingly uncertain because of diminishing sample size.

The series have considerable variability at decadal and longer time scales, but no regular periodicity. Spectral analysis failed to indicate statistically significant periodicity in tree-ring index.

**Table 3.** Loadings on tree-ring sites from a principal components analysis[1] of the eight Peace-Athabasca Delta tree-ring chronologies

| Site | PC#1 | PC#2 | PC#3 | PC#4 | PC#5 | PC#6 | PC#7 | PC#8 |
|---|---|---|---|---|---|---|---|---|
| **PPT** | 0.40 | 0.08 | -0.01 | 0.15 | 0.41 | 0.43 | 0.23 | 0.64 |
| **QFS** | 0.38 | -0.11 | -0.11 | 0.20 | 0.42 | -0.51 | -0.60 | 0.01 |
| **HRS** | 0.39 | 0.08 | 0.25 | -0.18 | -0.10 | -0.62 | 0.59 | 0.07 |
| **CPE** | 0.34 | 0.46 | 0.22 | -0.39 | -0.45 | 0.13 | -0.46 | 0.19 |
| **PRC** | 0.39 | 0.29 | 0.23 | 0.16 | 0.25 | 0.30 | 0.11 | -0.72 |
| **ATH** | 0.31 | -0.46 | -0.39 | -0.68 | 0.10 | 0.17 | 0.04 | -0.18 |
| **BIR** | 0.32 | 0.13 | -0.69 | 0.41 | -0.46 | -0.00 | 0.12 | -0.05 |
| **MAW** | 0.28 | -0.67 | 0.43 | 0.31 | -0.39 | 0.16 | -0.08 | 0.01 |
| **%Var**[2] | 62.71 | 10.04 | 7.86 | 6.35 | 5.30 | 3.74 | 2.61 | 1.39 |

[1]The principal components analysis was run on the correlation matrix of the eight standard chronologies for the period 1801-2000

[2]Percentage of total variance of the tree-ring data accounted for by each component

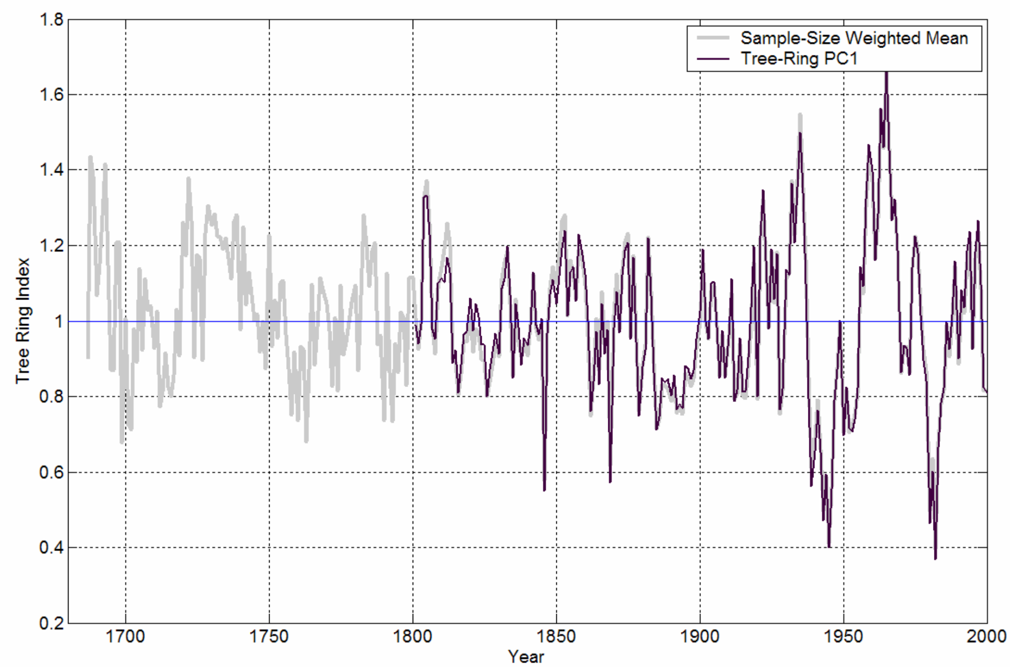



**Figure 8**. Summary plots of time series variations in delta tree-ring indices. Series scaled to have same mean and standard deviation before plotting.

## 5.3 Hydrologic Signal In Tree-Ring Data

**Peace-Athabasca Delta chronologies.** The relationships between tree-ring index and various hydrologic and climatic series were tested by a correlation analysis with the key variable the sample-size-weighted mean chronology plotted in Figure 8.

Product-moment correlation coefficients were computed between the delta-mean tree-ring series and three climatic series: total precipitation for the water year, maximum snow depth recorded in the first two weeks of April, and summer (June-September) mean temperature. Correlations were computed on whatever data were available in the 33-year period 1967-99. This analysis period is short for such an analysis, but is dictated by the length of the Ft. Chipewyan climatic record.

Results of the correlation analysis are summarized in a scatterplot matrix (Figure 9). For comparison, correlations and scatterplots are also shown for the water level (10-day mean, July 11-20) at Ft. Chipewyan for the same period. Data on which the scatterplots are computed are listed in Table 4. The tree-ring index is significantly correlated ($(r = 0.40,\ p-\text{value} < 0.05)$ with water level at Ft. Chipewyan, but not with any of the three climatic variables. Correlation is negative with summer temperature and positive with annual precipitation, though the correlations are not significant. The pattern of correlation is, however, consistent with a drought response: low water level and hot dry conditions associated with below normal tree growth.

The only other significant correlation in the scatterplot matrix is a positive relationship $(r = 0.44,\ p-\text{value} < 0.05)$ between annual precipitation and water level. This correlation probably results from the dependence of lake water level to some extent on the local precipitation and runoff input to the lake.

**All chronologies.** A second product-moment correlation analysis was run to evaluate the relative strength of relationship between each of the 54 tree-ring chronologies and three hydrologic series: 1) water level of Lake Athabasca, 2) annual streamflow of the Peace River at Peace River, and 3) annual streamflow of the Athabasca River at Athabasca. The lake level series is the 10-day mean for July 11-20. The streamflow series are water-year totals. Because one objective of this study was water-level and streamflow reconstruction, the correlation analysis also served to screen potential predictor tree-ring chronologies for reconstruction models.

The period for the correlation analysis was restricted to 1916-67, which covers the available streamflow period for the Peace River at Peace River prior to distortion of the record by W. A. C. Bennett Dam. Ideally, the period for computation of the correlation coefficients would be the same for all chronologies, but because of gaps in the hydrologic records, this was impossible. The maximum possible sample size (number of years) for correlation is less than 51 years: 34 years for lake level, 25 years for Peace River flow and 31 years for Athabasca River flow. Tree-ring series that end in 1965 have two fewer

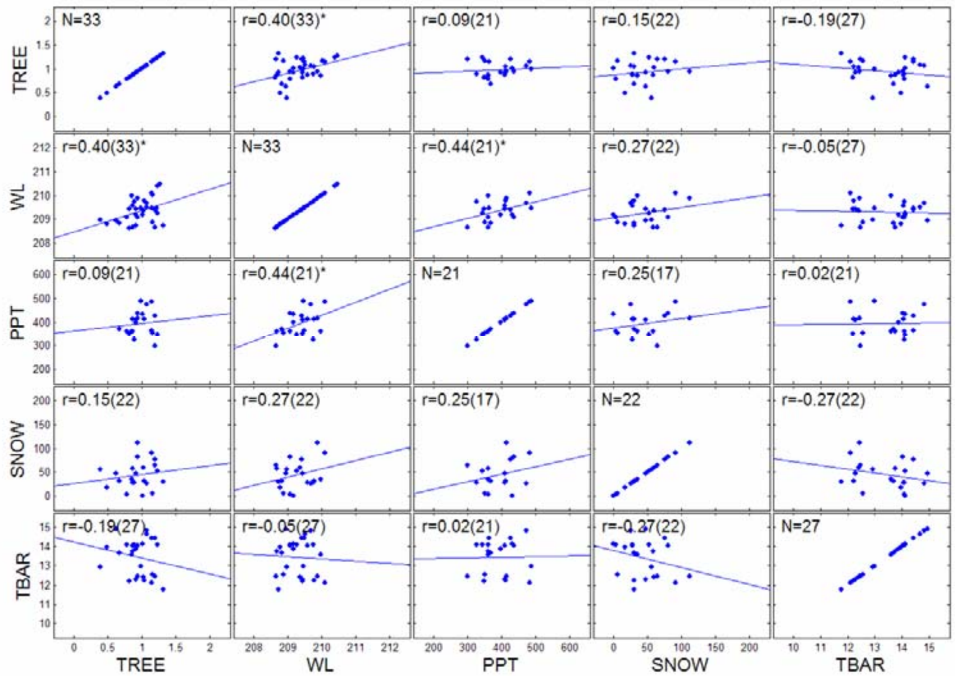



**Figure 9**. Scatterplot matrix of delta-mean tree-ring chronology and selected hydrologic and climatic variables. “TREE” is the sample-size-weighted mean tree-ring chronology based on the eight delta tree-ring sites. “WL” is the 10-day-mean (July 11-20) water level of Lake Athabasca at Ft. Chipewyan. “PPT” is annual (water-year) total precipitation at Ft. Chipewyan. “SNOW” is the maximum snow depth in the first two weeks of April each year. “TBAR” is the mean temperature for months June through September, computed from daily means. Correlations are based on whatever paired observations are available for the period 1967-99. Correlations are annotated at the top of each plot along with the sample size in parentheses and a symbol for significance (** for 0.01 level, * for 0.05) of correlation coefficient as estimated by a two-tailed test with null hypothesis of zero population correlation (Benjamin and Cornell 1970).

**Table 4.** Listing of tree-ring, hydrologic, and Ft. Chipewyan climatic data for scatterplot matrix.

| YEARS[1] | TREE RING[2] | WATER LEVEL(m)[3] | PPT(mm)[4] | SNOW DEPTH(cm)[5] | SUMMER T(°C)[6] |
|---|---|---|---|---|---|
| 1967 | 1.265 | 210.46 | NaN | NaN | NaN |
| 1968 | 1.312 | 208.73 | NaN | 30.0 | 11.8 |
| 1969 | 1.198 | 208.65 | 298.9 | 64.0 | 12.5 |
| 1970 | 0.870 | 208.67 | 359.9 | 58.0 | 13.7 |
| 1971 | 0.933 | 209.07 | 437.4 | 81.0 | 14.0 |
| 1972 | 0.934 | 209.88 | 415.1 | 112.0 | 12.5 |
| 1973 | 0.871 | 209.58 | 410.8 | 28.0 | 14.1 |
| 1974 | 1.150 | 210.09 | 483.3 | 91.0 | 12.1 |
| 1975 | 1.231 | 209.26 | 344.9 | 53.0 | 14.1 |
| 1976 | 1.193 | 209.40 | 426.4 | 76.0 | 14.4 |
| 1977 | 1.038 | 209.78 | 411.6 | 31.0 | 12.2 |
| 1978 | 0.919 | 209.44 | 409.5 | 48.0 | 12.3 |
| 1979 | 0.857 | 209.98 | 361.1 | 35.0 | 13.6 |
| 1980 | 0.487 | 208.79 | NaN | 17.0 | 14.0 |
| 1981 | 0.622 | 208.94 | NaN | 47.0 | 14.9 |
| 1982 | 0.386 | 208.97 | NaN | 56.0 | 12.9 |
| 1983 | 0.672 | 208.82 | 369.1 | 31.0 | 13.7 |
| 1984 | 0.778 | 209.08 | 360.7 | 4.0 | 14.1 |
| 1985 | 0.822 | 209.44 | 349.7 | NaN | 12.2 |
| 1986 | 0.989 | 209.46 | 488.5 | NaN | 13.0 |
| 1987 | 0.916 | 209.17 | 397.2 | NaN | 13.9 |
| 1988 | 1.010 | 209.18 | 432.2 | 0.0 | 14.1 |
| 1989 | 1.149 | 209.48 | 363.1 | NaN | 14.4 |
| 1990 | 0.896 | 209.75 | 326.6 | 28.0 | 14.1 |
| 1991 | 1.068 | 209.68 | 474.2 | 26.0 | 14.8 |
| 1992 | 1.026 | 209.36 | NaN | 60.0 | 12.4 |
| 1993 | 1.161 | 208.88 | 352.3 | 6.0 | 12.6 |
| 1994 | 1.215 | 209.47 | NaN | NaN | NaN |
| 1995 | 0.917 | 208.74 | NaN | NaN | NaN |
| 1996 | 1.163 | 210.02 | NaN | NaN | NaN |
| 1997 | 1.235 | 210.39 | NaN | NaN | NaN |
| 1998 | 1.078 | 209.50 | NaN | NaN | 14.7 |
| 1999 | 0.823 | 208.64 | NaN | NaN | NaN |

[1]Year of tree-ring formation
[2]"delta-mean" tree-ring index as defined in text
[3]Mean water level for July 11-20 at Ft. Chipewyan
[4]Annual precipitation total for water year (Oct 1 – Sept 30) ending in year of tree-ring
[5]Maximum daily snow depth in first two weeks of April
[6]Average daily mean temperature for period June 1-Sept 30
[7]"not a number" – incomplete daily data available to compute value for time series

years available for correlation. For weak statistical significance ($\alpha$-level = 0.05) between two time series, the approximate level of required correlation is $r = .35$ for $N$=34 and $r = 0.42$ for $N$=23 (Panofsky and Brier 1958).

Correlation coefficients between chronologies and hydrologic series are listed in Table 5 and mapped in Figures 10a, 10b and 10c. The highest single correlation coeffient is 0.73, between water level of Lake Athabasca and tree-ring series 6, a white spruce site along the Athabasca River in the Peace-Athabasca Delta.

The chronologies most strongly correlated with the water level of Lake Athabasca are those within the delta (Figure 10a). In fact, the highest seven mapped correlations in the 54-site network are for delta chronologies. Chronologies outside the delta are generally uncorrelated with water level of Lake Athabasca, and there is some indication of negative correlation between Athabasca Lake water level and chronologies south of about 53˚N.

The chronologies most strongly correlated with Peace River annual flow are also located in the delta, but are restricted to sites most directly connected hydrologically with the Peace River (Figure 10b). Sites 1, 2 and 5 have correlations exceeding 0.66 (Table 5). Sites 1 and 5 are along the Peace River; site 5 is a linear collection of trees along the Quatre Fourches channel (Figure 5). A few chronologies outside the delta also are highly correlated with Peace River flow. These are generally more northern chronologies, including sites along the Peace, Slave and Mackenzie Rivers, and some in the Canadian Rockies as far south as 52˚N (Spring Lake, site 47).

Chronologies most strongly correlated with Athabasca River annual flow are predominantly south of 53˚N (Figure 10c). Chronologies from the Peace-Athabasca Delta (inset map) are notable for their near-zero correlation with Athabasca River flow. Chronologies with exceptionally strong Athabasca River signal include Towers Ridge and Pyramid Lake (sites 17 and 22), in the southern Canadian Rockies.

The patterns of mapped correlations in Figure 10a-c are reasonable climatologically and hydrologically. Delta chronologies are most directly connected to the water level of Lake Athabasca, with rising and falling lake levels directly affecting water supply to the root zones of trees. Those delta chronologies along the Peace River and channels connected to the Peace River also might be expected to directly sense soil moisture variations associated with rising and falling flows of the Peace River. Peace River and Athabasca River flows depend largely on water supply from runoff in the Canadian Rockies. Drought-sensitive chronologies there are influenced by precipitation and temperature variations such that hot dry conditions are associated with low growth.

Negative correlations between some chronologies and streamflow are also plausible, especially for high-elevation sites whose growth might be limited in years with high snowpack and cool temperatures (Fritts 1976).

**Table 5**. Correlations of tree-ring chronologies with hydrologic series, 1916-67[1]

| N[2] | File[3] | Name[4] | Species[5] | Location[6] Lat | Lon | Elev | Period[7] First | Last | Correlation Coefficient[8] Lake Level | Peace R. | Ath. R. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | PPTWT1 | PPT, POINT PROVIDENCE | PCGL | 59.0 | -112.0 | 209 | 1698 | 2000 | 0.67(34) | 0.67(25) | 0.09(31) |
| 2 | QFSWT1 | QFS, QUATRE FOURCHES | PCGL | 58.8 | -111.5 | 209 | 1712 | 2000 | 0.68(34) | 0.70(25) | -0.01(31) |
| 3 | HRSWT1 | HRS, HORSESHOE SLOUGH | PCGL | 58.9 | -111.6 | 209 | 1801 | 2000 | 0.63(34) | 0.45(25) | -0.22(31) |
| 4 | CPEWT1 | CPE, REVILLON COUPE | PCGL | 58.9 | -111.4 | 209 | 1742 | 2000 | 0.62(34) | 0.34(25) | 0.03(31) |
| 5 | PRCWT1 | PRC, PEACE/ROCHERS | PCGL | 59.0 | -111.4 | 209 | 1687 | 2000 | 0.70(34) | 0.65(25) | 0.02(31) |
| 6 | ATHWT1 | ATH, ATHABASCA RIVER | PCGL | 58.4 | -111.5 | 209 | 1708 | 2000 | 0.73(34) | 0.30(25) | -0.14(31) |
| 7 | BIRWT1 | BIR, BIRCH RIVER | PCGL | 58.5 | -112.5 | 209 | 1757 | 2000 | 0.40(34) | 0.48(25) | -0.05(31) |
| 8 | MAWWT1 | MAW, MAMAWI LAKE | PCGL | 58.6 | -111.3 | 209 | 1801 | 2000 | 0.67(34) | 0.37(25) | -0.23(31) |
| 9 | CANA008 | THELON GAME SANCTUAR | PCGL | 63.8 | -104.2 | 207 | 1574 | 1969 | -0.11(34) | -0.12(25) | -0.08(31) |
| 10 | CANA155 | HORNBY CABIN | PCGL | 64.0 | -103.9 | 160 | 1491 | 1984 | -0.21(34) | -0.38(25) | -0.04(31) |
| 11 | CANA156 | MACKENZIE MOUNTAINS | PCGL | 65.0 | -127.8 | 1375 | 1626 | 1984 | 0.14(34) | 0.56(25) | 0.18(31) |
| 12 | CANA129 | WOOD BUFF SF | PCGL | 60.0 | -112.3 | 200 | 1833 | 1989 | 0.37(34) | 0.33(25) | -0.22(31) |
| 13 | CANA130 | WOOD BUFF RL | PCGL | 59.8 | -112.2 | 250 | 1846 | 1989 | 0.44(34) | 0.59(25) | -0.07(31) |
| 14 | CANA131 | WOOD BUFF BR | PCGL | 59.1 | -112.2 | 240 | 1866 | 1989 | 0.57(34) | 0.66(25) | 0.01(31) |
| 15 | CANA132 | WOOD BUFF PR | PIBN | 59.8 | -112.2 | 300 | 1852 | 1992 | 0.27(34) | 0.07(25) | 0.03(31) |
| 16 | CANA133 | WOOD BUFF NL | PIBN | 59.6 | -111.3 | 220 | 1857 | 1992 | 0.22(34) | 0.02(25) | -0.05(31) |
| 17 | CANA135 | TOWERS RIDGE | PIFL | 51.2 | -114.7 | 1250 | 1315 | 1992 | -0.03(34) | 0.27(25) | 0.63(31) |
| 18 | CANA012 | KAMLOOPS_PSME+FRASER | PSME | 50.8 | -120.6 | 822 | 1420 | 1965 | -0.13(32) | -0.08(23) | 0.16(29) |
| 19 | CANA015 | KAMLOOPS_PIPO | PIPO | 50.8 | -120.6 | 822 | 1590 | 1965 | -0.24(32) | 0.17(23) | 0.22(29) |
| 20 | CANA020 | POWERHOUSE, ALBERTA | PSME | 51.2 | -115.5 | 1432 | 1410 | 1965 | 0.10(32) | 0.15(23) | 0.25(29) |
| 21 | CANA022 | EXSHAW+TUNNEL+BANFF, | PSME | 51.2 | -115.6 | 1310 | 1460 | 1965 | 0.12(32) | 0.31(23) | 0.26(29) |
| 22 | CANA026 | PYRAMID LAKE+PATRICI | PSME | 52.9 | -118.1 | 1128 | 1540 | 1965 | 0.37(32) | 0.61(23) | 0.52(29) |
| 23 | CANA147 | SICAMOUS CREEK, BRIT | PCEN | 50.8 | -119.9 | 1550 | 1665 | 1994 | -0.25(34) | 0.12(25) | 0.11(31) |
| 24 | CANA161 | ADAMS LAKE PCEN | PCEN | 51.0 | -119.1 | 1900 | 1710 | 1996 | -0.36(34) | -0.00(25) | -0.04(31) |
| 25 | CANA162 | ADAMS LAKE ABLA | ABLA | 51.0 | -119.1 | 1900 | 1773 | 1996 | -0.36(34) | -0.05(25) | -0.13(31) |
| 26 | CANA174 | MOUNT CAIN | ABAM | 50.2 | -126.3 | 1005 | 1420 | 1999 | 0.21(34) | 0.06(25) | -0.00(31) |
| 27 | CANA038 | BRUNO LAKE, MANITOBA | PCGL | 51.6 | -95.8 | 1000 | 1822 | 1988 | -0.01(34) | 0.20(25) | 0.41(31) |
| 28 | CANA039 | GUNISAO LAKE | PCMA | 53.5 | -96.4 | 860 | 1819 | 1988 | -0.15(34) | -0.07(25) | 0.25(31) |
| 29 | CANA044 | WILLOW LAKE | PCMA | 62.2 | -119.1 | 620 | 1850 | 1988 | 0.08(34) | 0.13(25) | 0.12(31) |
| 30 | CANA047 | FORT PROVIDENCE | PCGL | 61.2 | -117.4 | 500 | 1829 | 1988 | 0.31(34) | 0.37(25) | -0.21(31) |
| 31 | CANA048 | FORT SIMPSON MCKENZI | PCGL | 61.7 | -120.7 | 375 | 1821 | 1988 | 0.03(34) | 0.29(25) | -0.40(31) |
| 32 | CANA052 | BRAS D'OR LAKE (INSE | PCGL | 62.5 | -116.1 | 700 | 1759 | 1988 | 0.28(34) | 0.11(25) | 0.09(31) |
| 33 | CANA053 | PETHAI PENINSULA | PCGL | 62.7 | -111.0 | 1400 | 1610 | 1988 | 0.39(34) | 0.08(25) | 0.34(31) |

**Table 5**. Correlations of tree-ring chronologies with hydrologic series, 1916-67[1] (continued)

| | | | | Location[6] | | | Period[7] | | Correlation Coefficient[8] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| N[2] | File[3] | Name[4] | Species[5] | Lat | Lon | Elev | First | Last | Lake Level | Peace R. | Ath. R. |
| 34 | CANA057 | FORT SIMPSON MCKENZI | PCGL | 61.7 | -120.7 | 375 | 1807 | 1988 | 0.05(34) | 0.43(25) | -0.29(31) |
| 35 | CANA058 | AUSTIN LAKE | PCGL | 62.2 | -110.1 | 850 | 1818 | 1988 | 0.15(34) | -0.26(25) | 0.12(31) |
| 36 | CANA070 | CHARLIE LAKE | PCMA | 60.0 | -100.4 | 1055 | 1768 | 1988 | 0.14(34) | 0.28(25) | 0.16(31) |
| 37 | CANA074 | BUFFALO LAKE | PCGL | 60.3 | -115.3 | 803 | 1842 | 1988 | 0.37(34) | 0.60(25) | 0.10(31) |
| 38 | CANA085 | CASSIAR | PCGL | 59.1 | -129.9 | 900 | 1817 | 1983 | -0.32(34) | 0.38(25) | 0.08(31) |
| 39 | CANA086 | GNAT PASS, DEASE LAK | PCGL | 58.3 | -129.9 | 1200 | 1757 | 1983 | -0.20(34) | -0.02(25) | 0.05(31) |
| 40 | CANA087 | WATSON LAKE | PCGL | 60.1 | -128.8 | 750 | 1742 | 1983 | 0.16(34) | 0.16(25) | 0.07(31) |
| 41 | CANA088 | SUMMIT LAKE PASS | PCGL | 58.7 | -124.7 | 1260 | 1770 | 1983 | 0.29(34) | 0.36(25) | 0.05(31) |
| 42 | CANA089 | FORT NELSON | PCGL | 58.3 | -122.8 | 690 | 1817 | 1983 | 0.18(34) | 0.46(25) | 0.21(31) |
| 43 | CANA091 | SMITHERS SKI AREA | PCGL | 54.9 | -127.3 | 1200 | 1680 | 1983 | -0.14(34) | -0.33(25) | 0.15(31) |
| 44 | CANA092 | PINE PASS | PCGL | 55.5 | -122.7 | 780 | 1697 | 1983 | -0.26(34) | 0.19(25) | 0.16(31) |
| 45 | CANA093 | BEAR LAKE | PSME | 54.5 | -122.5 | 690 | 1773 | 1983 | -0.15(34) | 0.33(25) | 0.30(31) |
| 46 | CANA094 | BELL MOUNTAIN | PCEN | 53.3 | -120.7 | 1530 | 1652 | 1983 | -0.14(34) | -0.30(25) | 0.02(31) |
| 47 | CANA095 | SPRING LAKE | PSME | 51.9 | -121.3 | 810 | 1669 | 1983 | 0.17(34) | 0.48(25) | 0.27(31) |
| 48 | CANA096 | SUNWAPTA PASS | PCEN | 52.3 | -117.0 | 2000 | 1608 | 1983 | -0.13(34) | -0.06(25) | 0.16(31) |
| 49 | CANA097 | PEYTO LAKE | PCEN | 51.8 | -116.2 | 2050 | 1634 | 1983 | 0.02(34) | 0.15(25) | 0.02(31) |
| 50 | CANA098 | VERMILION PASS | PCEN | 51.2 | -116.2 | 1500 | 1686 | 1983 | -0.05(34) | 0.53(25) | 0.10(31) |
| 51 | CANA099 | SARRAIL GLACIER | PCEN | 50.6 | -115.2 | 2290 | 1499 | 1991 | -0.09(34) | -0.10(25) | -0.14(31) |
| 52 | CANA120 | KATHERINE CREEK N.W | PCGL | 65.0 | -127.5 | 680 | 1700 | 1989 | -0.09(34) | -0.18(25) | 0.05(31) |
| 53 | CANA124 | SKIPPING BULLET N.W | PCGL | 65.0 | -127.6 | 950 | 1780 | 1989 | 0.25(34) | 0.33(25) | 0.30(31) |
| 54 | WPPSTD | WHIRLPOOL POINT | PIFL | 52.0 | -116.5 | 1373 | 890 | 1996 | 0.29(34) | 0.15(25) | 0.37(31) |

[1]Actual period for correlations may be subset of 1916-67 depending on missing data
[2]Sequence number of chronology
[3]Computer file from which chronology extracted; sources as follows:
Series 1-8, collection from summer 2001
Series 9-53, International Tree-Ring Data Bank (ITRDB)
Series 54, Glen MacDonald and Rosalyn Case, contribution of unpublished data
[4]Chronology name, sometimes shortened or modified to facilitate reference
[5]Species code (see Appendix appspecies)
[6]Latitude and longitude (decimal degrees) and elvation (m above sea level); sites 12-16 incorrectly listed as 0 meters elevation in International Tree-Ring Data Bank -- elevations in this region generally about 210 m
[7]Year of coverage of the tree-ring standard chronology
[8]Product moment correlation coefficient, with sample size in parentheses

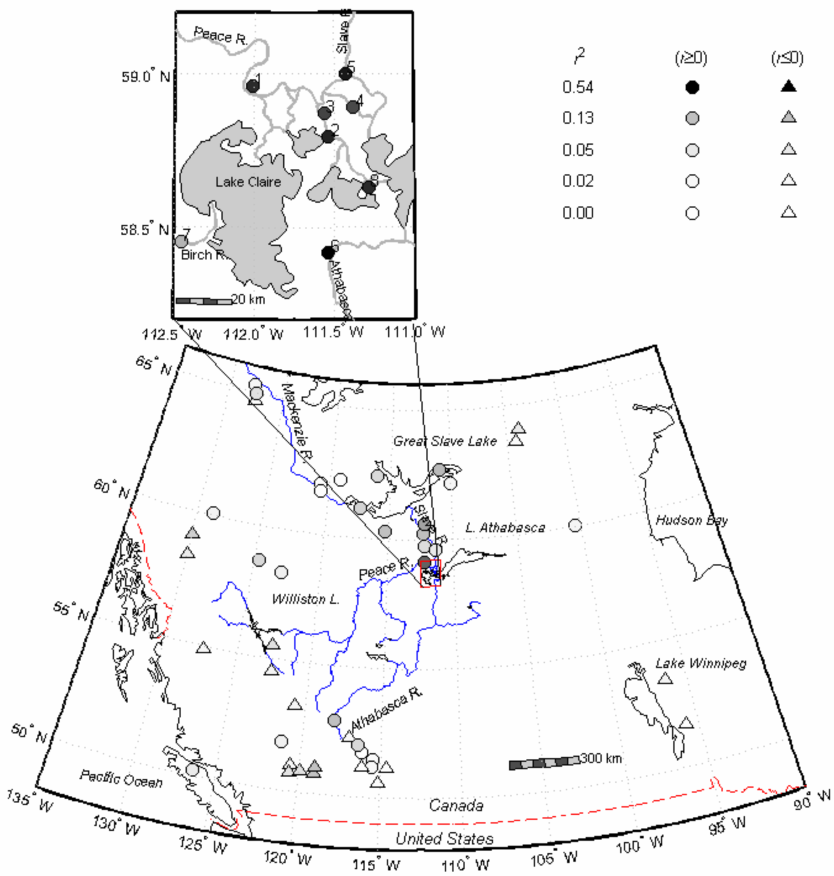



**Figure 10a.** Map showing strength of linear relationship between each of 54 tree-ring chronologies and the Lake Athabasca Water Level at Ft. Chipewyan. Sign of bivariate correlations (product-moment) is coded by symbol shape. Size of squared correlation is coded by gray shading (black=highest, white=0). Key shows shading levels for maximum, minimum, median, and first and third quartile of the 54 squared correlations. Correlation coefficients and sample sizes are listed in Table 5. Period for correlation restricted to 1916-67. Note that strongest signal is for the eight delta chronologies collected in summer, 2001 (inset map).

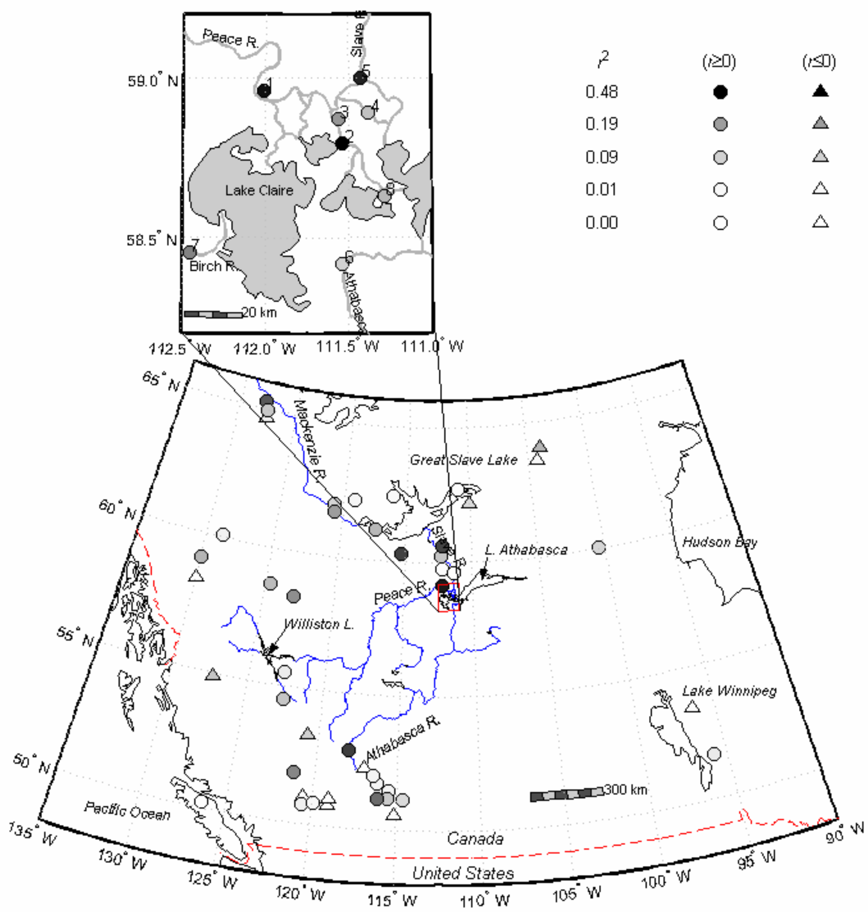



**Figure 10b.** Map showing strength of linear relationship between each of 54 tree-ring chronologies and streamflow (water-year total) of the Peace River at Peace River. Remainder of caption as in Figure 10a.

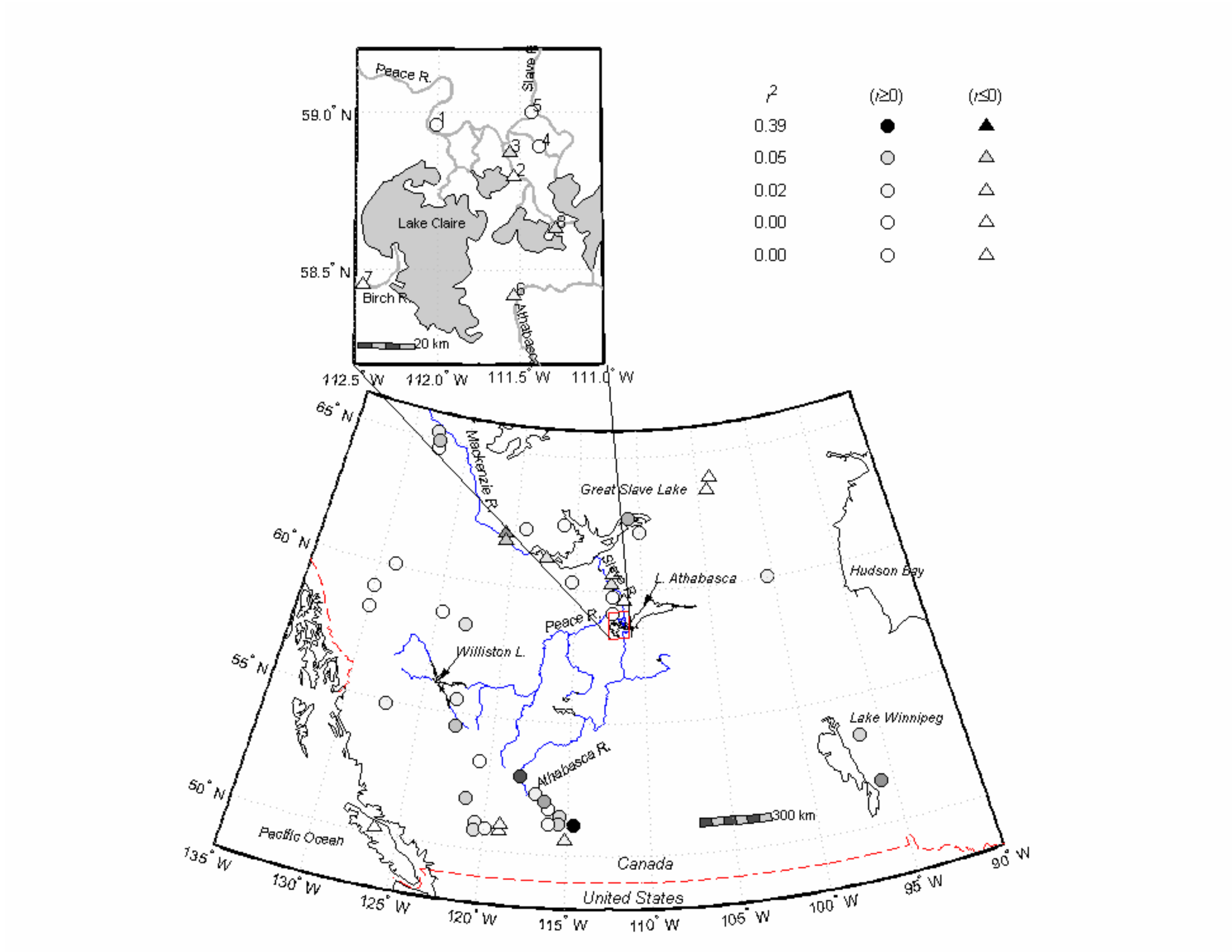



**Figure 10c.** Map showing strength of linear relationship between each of 54 tree-ring chronologies and streamflow (water-year total) of the Athabasca River at Athabasca. Remainder of caption as in Figure 10a.

### 5.4 Regression And Reconstruction

The correlation analysis just described was used as a guide in selecting calibration periods for the three reconstruction models: 1) Lake Athabasca water level (July 11-20), 2) Peace River annual flow, and 3) Athabasca River annual flow. The starting year for reconstructions was set at 1801 because drop-off in sample depth makes the tree-ring signal of the delta chronologies questionable before then. The requirement of an 1801 start year automatically eliminates many of the 54 chronologies as possible predictors (Table 5).

Some tree-ring series in Table 5 with relatively strong hydrologic signals were collected as early as 1965. Use of those sites in the regression model would constrain the calibration period for the model to the period ending in 1965. Considering the limitations on length of calibration period already imposed by the gaps in the annual flow series of both rivers, and the distortion of the record for the Peace River by Bennett Dam after 1967, sacrificing additional years from the calibration period would be unacceptable. After reviewing the time coverage and signal strength of the chronologies, The following calibration periods were selected:

| | |
|---|---|
| Lake Athabasca Water Level: | 1935-99 |
| Peace River streamflow: | 1916-67 (broken by gap) |
| Athabasca River streamflow: | 1915-92 (broken by gap, |

The correlation analysis summarized in Table 5 was then repeated separately for the 1915-92 period to allow greater sample size for correlations for screening chronologies for the Athabasca River model. Correlations generally decreased from the 1916-67 to the 1916-83 and 1915-92 periods, but for the most part the same chronologies were generally identified as having the strongest signals for all periods. For example, the correlation of Athabasca River flow with the Towers Ridge chronology (site 17) drops from 0.61 to 0.34 from the 1916-67 period to the 1915-92 period, but Towers Ridge is still the second-highest correlated chronology with Athabasca River flow for the 1915-92 period.

For Lake Athabasca water level, correlations suggested a “local” model for the water level reconstruction. In this model, the predictor pool is restricted to the 8 chronologies developed for the Peace Athabasca Delta from the 2001 field collections augmented by the earlier tree-ring collections of Stockton and Fritts (1973).

For the Peace River reconstruction, the correlations suggested that a “local/global” model, with useful predictive value coming from chronologies directly sensing rising and falling water levels (e.g., PPT and PRC along the Peace River in the delta) and from chronologies in runoff-producing areas in the upper reaches of the watershed.

For the Athabasca River reconstruction, a purely “global” model was suggested, as chronologies from the delta had no apparent signal for annual Athabasca River flow. The most likely effective predictors for this model are chronologies from the southern Canadian Rockies.

The coefficients of the final regression (reconstruction) models and model statistics are listed in Table 6. The Peace River reconstruction is by far the most accurate of the three, with a regression $R^2$ of 0.60. Calibration accuracy is much lower for the lake level ($R^2 = 0.36$) and Athabasca River streamflow ($R^2 = 0.25$) reconstructions. The three models are fairly simple, each having only two predictors, although these are sometimes weighted combinations of more than one tree-ring chronology. The *F*-levels for all three models are highly significant (*p*-value<0.001). All three reconstructions show positive skill of verification as measured by the reduction-of-error statistic computed for cross-validation. Where more than one row of model statistics is listed in Table 6, the statistics are the stepwise results. For example, for lake level, the RE statistic was 0.25 for a model with just one predictor, and rose to 0.29 after the second predictor entered. The individual models are described in more detail individually below.

**Regression model for water level of Lake Athabasca.** The pool of potential predictors for this model included the first two PCs of the 8 delta chronologies at lags 0 and +1 years relative to the year of water-level measurement. These PCs have already been described (Table 3). The first two PCs effectively summarize most of the common variance in the delta tree-ring chronologies. The positive lag was included to allow for the possibility of a lag effect between water supply and growth variation. The lake level reconstruction model is the only one of the three models that uses any lagged predictors. (Lags were not feasible for the other models because of gaps in the calibration time series of the predictands.)

The 65-year calibration period is 1935-99. The calibration period begins with 1935 rather than 1934 because the 1934 observed lake-level series is based on sparse data. The 1999 end year is the last year that would accommodate a +1 year lag on the predictors for tree-ring series ending in 2000. The entire water-level record, rather than just the pre-Bennett record, was used for correlation because both the flow at Peace River and the water level variations sensed by the trees at the delta sites are both presumably affected by the presence of the dam.

The final equation has two predictors: PC's 1 and 2 of the eight delta tree-ring chronologies. The most important predictor, PC1, enters at lag zero with a positive weight. Recall that PC1 has positive weights on all eight chronologies, and is a therefore a proxy for delta-wide tree-ring variation (Table 3). This predictor probably reflects an overall positive relationship between moisture availability to the trees and tree growth. PC2 represents north-south contrast in growth across the delta (Table 3), and enters the equation at lag +1 year, possibly reflecting a delay in response due to the inertia in the tree biology or the hydrology (e.g., water levels in summer of one year still affecting tree vigor the following year).

Plots summarizing the agreement of observed and reconstructed water level in the calibration period are shown in Figure 11a. The time series plots show that the

**Table 6.** Regression coefficients and statistics of reconstruction models.

| | Equation[2] | | | Model Statistics: Calibration[3] | | | | Validation[4] | |
|---|---|---|---|---|---|---|---|---|---|
| **Predictand[1]** | **Step** | **Predictor** | **b** | **$R^2$(adj)** | **N** | **F** | **$RMSE_c$** | **$RMSE_v$** | **RE** |
| **Lake Level** | 0 | --- | +2.095E+002 | | | | | | |
| | 1 | PAD_PC1-L0 | +2.604E-001 | 0.32(0.32) | | | 5.002e-001 | 5.172e-001 | 0.25 |
| | 2 | PAD_PC2-L1 | +1.541E-001 | 0.36(0.35) | 65 | 17.5 | 4.893e-001 | 5.049e-001 | 0.29 |
| **Peace R.** | 0 | --- | +1.229E+003 | | | | | | |
| | 1 | PPT/PRC | +1.449E+002 | 0.45(0.45) | | | 2.450e+002 | 2.594e+002 | 0.33 |
| | 2 | SPRING LAKE | +4.920E+002 | 0.60(0.58) | 25 | 16.4 | 2.134e+002 | 2.311e+002 | 0.47 |
| **Athabasca R.** | 0 | --- | +5.484E+002 | | | | | | |
| | 1 | ATH_PC2 | +4.121E+001 | 0.21(0.21) | | | 7.677e+001 | 7.811e+001 | 0.15 |
| | 2 | SICAMOUS CREEK | -1.200E+002 | 0.25(0.24) | 57 | 9.2 | 7.502e+001 | 7.751e+001 | 0.16 |

[1]"Lake Level" is the level of Lake Athabasca at Ft. Chipewyan. "Peace R." is the annual total (water year) gaged flow of the Peace River at Peace River. "Athabasca R." is the annual total (water year) gaged flow of the Athabasca River at Athabasca.

[2]Entries include the step in the forward stepwise regression at which the predictor entered, the name of the predictor (see text for details), and the estimated coefficients of the regression model. The constant term in the regression model is listed at step "0."

[3]Calibration statistics listed are the coefficient of multiple determination, or regression $R^2$, the sample size (number of years) for calibrating the model, the $F$-level of the final equation, and the root-mean-square-error of calibration – equivalent to the standard error of the estimate.

[4]Validation statistics listed are the root-mean-square-error of validation ($RMSE_v$) and the reduction of error statistic (RE), both derived by leave-one-out cross-validation

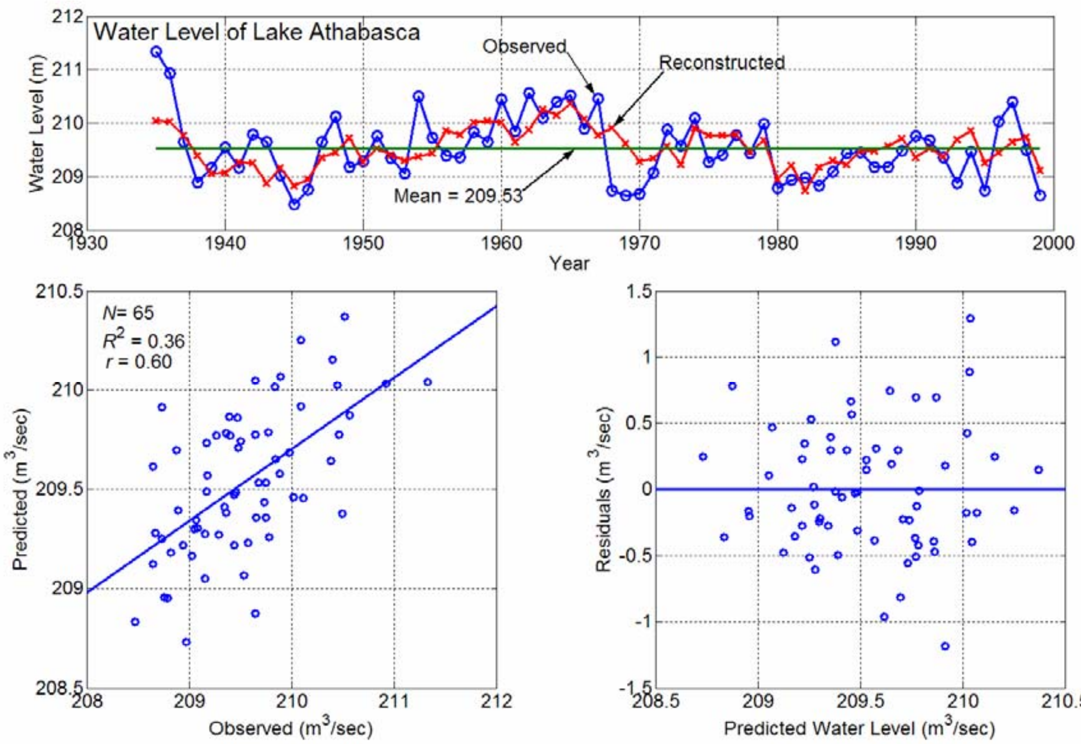



**Figure 11a.** Calibration-period diagnostic plots for Lake Athabasca water-level reconstruction model. Top: time series plots of observed and reconstructed water level for years used in calibration, with horizontal line at calibration-period mean. Lower left: scatterplot of predicted water level against observed water level, with sample size, regression $R^2$ and correlation between predicted and observe series annotated. Lower right: time series plot of residuals (observed minus predicted water level) against predicted water level.

reconstruction generally tracks the observed data closely, especially the gradual swings between extended period of high and low water level. The reconstruction effectively identifies low water levels in the mid-1940s, high water levels in the mid-1960s, and low water levels in the early 1980s.

Some individual years are poorly reconstructed. Examples are the magnitudes of the highs in 1935-36, 1954, and 1996-97 and the lows in 1968-70. Underestimation of extremes is expected for any MLR model, especially one with an $R^2$ as low as 0.36. It is also possible that the positive tree-ring response to additional moisture weakens under very high water levels as water might be expected to become less limiting to growth then. Exploratory analysis using scatterplots (not shown) of the individual delta chronologies against water level did not, however, show a curvature indicating flattening out of the relationship toward higher water levels. The low observed water levels in 1968-70 occurred during the filling period of Bennett Dam. Why the tree-ring series miss this low-flow period is uncertain. Possibly the favorable moisture conditions of the mid-1960s in the delta carried over to 1970s at some of the tree-ring sites, so that trees did not suffer severe water stress by 1970.

The cloud of points in the scatterplot of predicted vs observed water level (Figure 11a, lower left), as expected for a significant relationship, shows a clear pattern with a positive slope rather than loose scatter along a horizontal line. This plot also shows that the relationship is inherent in the mass of points rather than driven by a few outliers. The scatterplot of residual against predicted values (Figure 11a, lower right) shows no apparent relationship between residuals and predicted values. A pronounced pattern (e.g. fanning out of residuals from left to right) would indicate that that the predictand or predictors should be transformed (e.g., log-transform) before regression (Weisberg 1985).

Lagged scatterplots and a Durbin-Watson test of residuals (Draper and Smith 1981) indicated that the assumption of non-autocorreation of residuals is not violated. Lilliefors test (Conover 1980) applied to the regression residuals indicated that the assumption of normality cannot be rejected at the 0.01 alpha-level.

**Regression model for annual streamflow of Peace River.** The time constaint (1801-1967) and correlation screening (Table 5) yielded a set of 12 chronologies as possible predictor variables. Numbered as in Table 5, those chronologies are:

| | |
|---|---|
| 1 PPT | 8 MAW |
| 2 QFS | 10 HORNBY CABIN |
| 3 HRS | 11 MACKENZIE MOUNTAINS |
| 4 CPE | 41 SUMMIT LAKE PASS |
| 5 PRC | 47 SPRING LAKE |
| 7 BIR | 50 VERMILION PASS |

A series of preliminary stepwise regression models was then run using various combinations of the chronologies and PCs of the chronologies. The physical plausibility of the resulting models as well as their performance in cross-validation were used to arrive at a much simplified final model with two predictors (Table 6).

The first predictor is PPT/PRC, which is a PC on just the two chronologies directly along the Peace River in the delta (PPT and PRC). PPT/PRC is the "local" predictor in the model, and presumably reflects direct sensing of streamflow variations by trees. The global predictor is tree-ring site 47 (Spring Lake), a Douglas-fir chronology positively related to moisture variation in the runoff-producing areas of the river

Plots summarizing the agreement of observed and reconstructed water level in the calibration period are shown in Figure 11b. A shortcoming of this model is the extremely short calibration period (25 yr): streamflow data are not available for 1932-1958, and streamflow data after 1967 are not suitable because of the expected change in the precipitation/streamflow relationship with Bennett Dam.

Both the time series plots of observed and reconstructed data (Figure 11b, top) and the corresponding scatterplot (Figure 11b, lower left) of predicted against observed streamflow indicate an extremely tight linear relationship, reflected in the calibration statistics ($R^2$=.60). Agreement in the 1960s is especially close. The most important outlier is 1920, when a moderately high observed flow coincides with one of the lowest reconstructed flows.

Results of an analysis of residuals are similar to the results for the water-level reconstruction : no apparent need to transform variables, no autocorrelation of residuals, and no strong evidence for rejecting a null hypothesis of normality of residuals.

**Regression model for annual streamflow of Athabasca River.** The time constraint (1801-1992) and correlation analysis (based on 1915-92 period) yielded a set of 5 chronologies as possible predictor variables. Numbered as in Table 5, those chronologies are:

3 HRS
6 ATH
17 TOWERS RIDGE
23 SICAMOUS CREEK, BRIT
24 ADAMS LAKE PCEN
54 WHIRLPOOL POINT

A PCA on the chronologies followed by trial-and-error stepwise regressions using the PCs and original chronologies as predictors indicated two useful predictors: 1) a PC with highest weights on Towers Ridge and Whirlpool Point, and 2) The Sicamous Creek chronology. The PCA was then re-run without Sicamous Creek and the regression repeated. Again a PC that strongly weights Towers Ridge and Whirlpool Point and the Sicmamous Creek chronology were selected as predictors. The first three PCs of the PCA are listed in Table 7. PC2 is the primary predictor for the Athabasca River

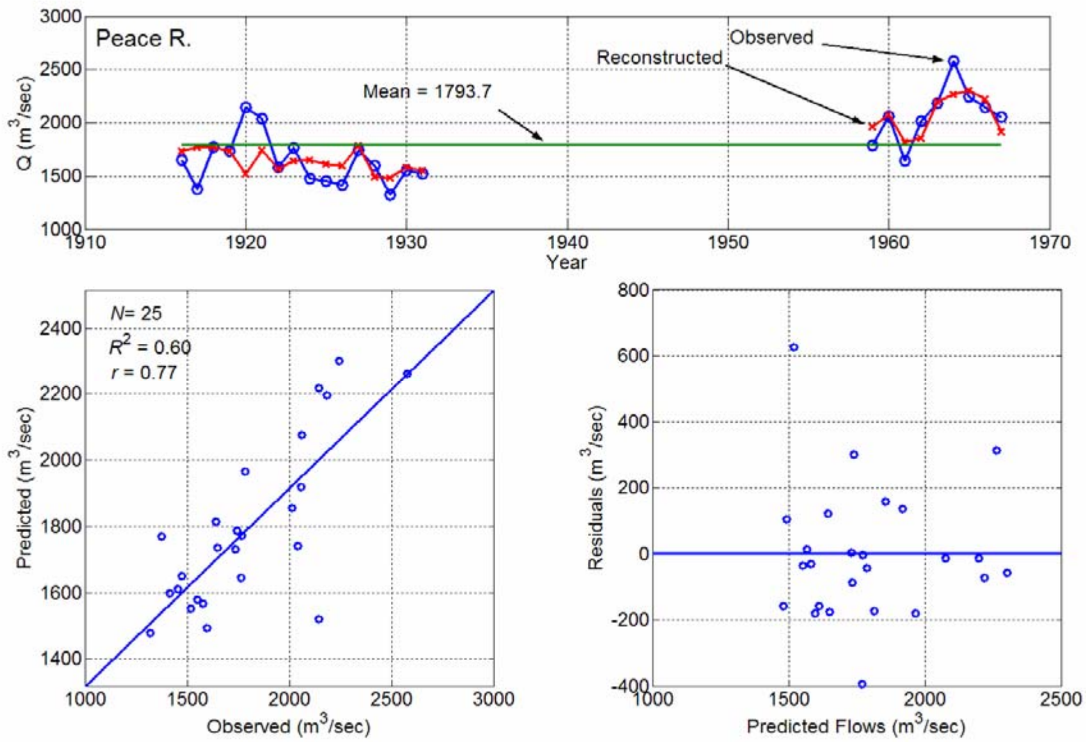



**Figure 11b.** Calibration-period diagnostic plots for Peace River annual streamflow reconstruction model. Top: time series plots of observed and reconstructed flow for years used in calibration, with horizontal line at calibration-period mean. Lower left: scatterplot of predicted flows against observed flows, with sample size, regression $R^2$ and correlation between predicted and observe series annotated. Lower right: Time series plot of residuals (observed minus predicted flow) against predicted flows.

**Table 7**. First three principal components[1] on chronologies most highly correlated with Athabasca River flow.

| Site | PC#1 | PC#2 | PC#3 |
|---|---|---|---|
| 3 HRS | 0.6700 | -0.2473 | -0.0465 |
| 6 ATH | 0.7009 | -0.0857 | -0.0326 |
| 17 TOWERS RIDGE | 0.1510 | **0.6848** | 0.2219 |
| 24 ADAMS LAKE PCEN | 0.0558 | -0.0471 | 0.9569 |
| 54 WHIRLPOOL POINT | 0.1842 | **0.6785** | -0.1786 |

[1]From a PCA on the correlation matrix of the time series for period 1801-1992

reconstruction. The Sicamous Creek tree-ring chronology is the second predictor to enter (Table 6).

Plots summarizing the agreement of observed and reconstructed water level in the calibration period are shown in Figure 11c. The Athabasca River record has a wide gap due to missing data, but the calibration period still covers 57 years (all years with annual flow data between 1915 and 1992).

The time series plots of observed and reconstructed data (Figure 11c, top) and the corresponding scatterplot (Figure 11c, lower left) reflect the relatively low accuracy of this reconstruction ( $R^2$=.25) compared with the Peace River reconstruction. Nevertheless, the regression is still has a highly statistically significant $F$-level and at times (e.g., the decade preceding the break in the record) tracks the observed record very closely. For example, the correlation of observed and reconstructed values between 1917 and 1930 is 0.65.

As with the Peace River reconstruction, a few high observed flows are severely underestimated. The years 1954 and 1965 are the best examples of underestimation of high flow. High flow in 1954 was also greatly underestimated in the Peace River reconstruction (Figure 11b). Another interesting feature shared with the Peace River reconstruction is the failure of the reconstruction to track a 3-year sequence of low flows in 1968-70. The fact that the observed flows for this period are low on the Athabasca River suggests that the extremely low water levels of Lake Athabasca during that period (Figure 11a) could possibly be due at least in part to reduced inflow from the Athabasca.

An analysis of residuals gave results similar to those for other two reconstructions: no apparent need to transform variables, no autocorrelation of residuals, and no strong evidence for rejecting the null hypothesis of normality of residuals.

## *5.5 Time Series Variations In Reconstructions*

**Annual variations.** The full-length time series of reconstructed hydrologic time series are plotted in Figure 12. The starting year for all three reconstructions is 1801. The ending year depends on the time coverage of tree-ring predictors in the models. The full reconstruction periods are as follows:

| | |
|---|---|
| Water Level, Lake Athabasca: | 1801-1999 |
| Annual flow, Peace R. | 1801-1983 |
| Annual flow, Athabasca R. | 1801-1992 |

All three reconstruction have considerable variability at time scales of decades and longer. The Lake Athabasca water level series and Peace River series share many prominent low-frequency features, such as the swing from record dry conditions in the 1940s to record wet conditions in the 1960s. Some similarity in these reconstructions is expected as their reconstruction models share some of the same

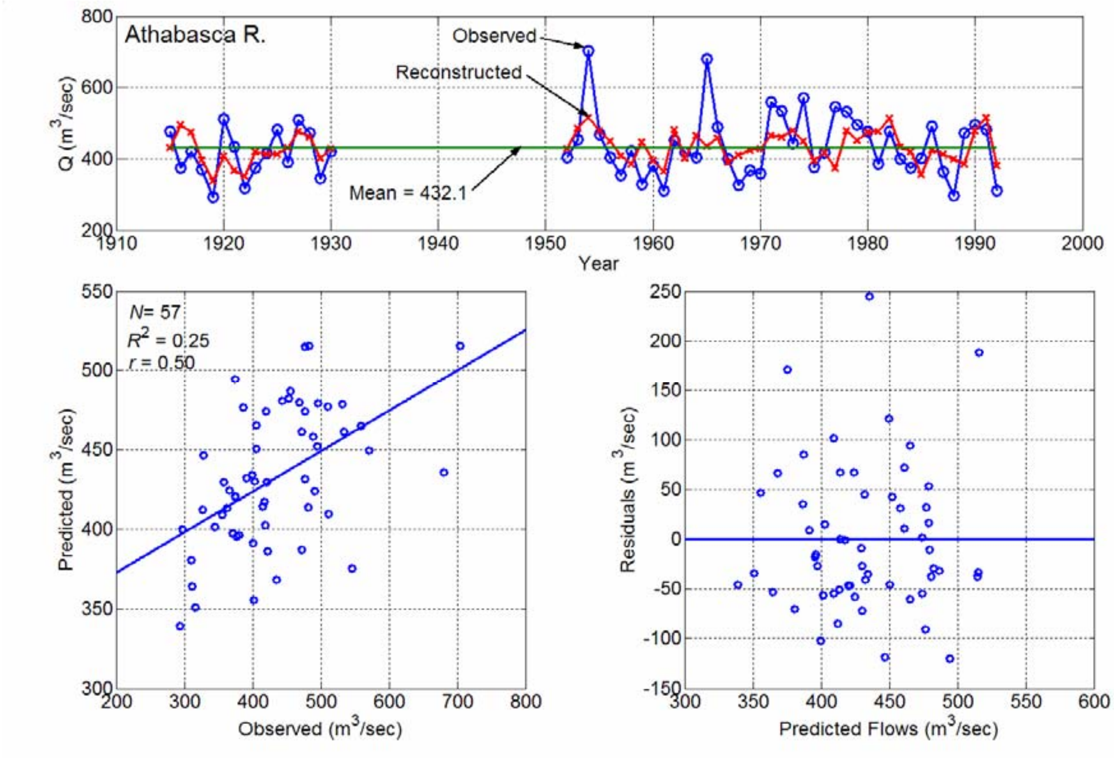



**Figure 11c.** Calibration-period diagnostic plots for Athabasca River annual streamflow reconstruction model. Top: time series plots of observed and reconstructed flow for years used in calibration, with horizontal line at calibration-period mean. Lower left: scatterplot of predicted flows against observed flows, with sample size, regression $R^2$ and correlation between predicted and observe series annotated. Lower right: Time series plot of residuals (observed minus predicted flow) against predicted flows.

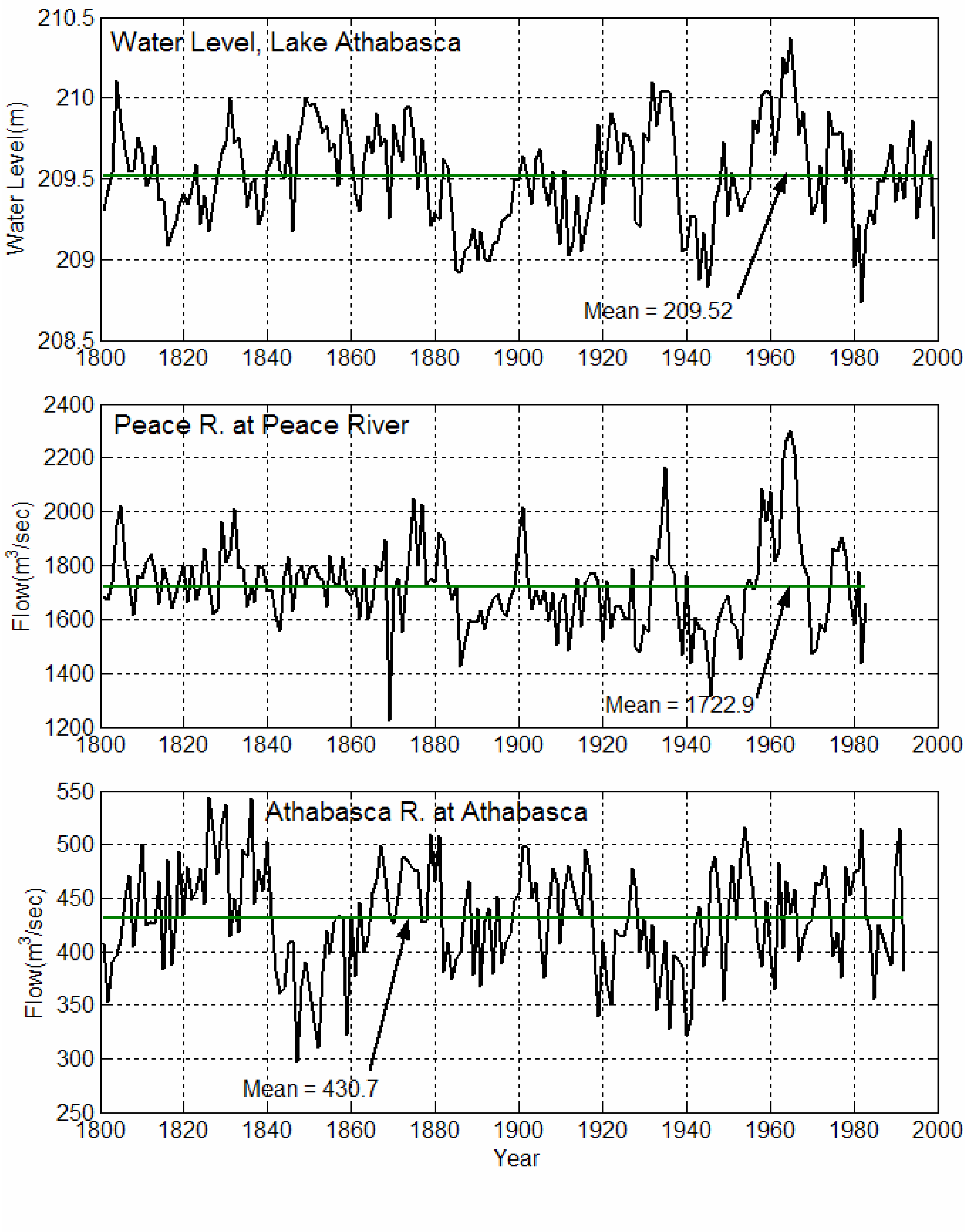



**Figure 12**. Time series plots of annual values (unsmoothed) of long-term hydrologic reconstructions. Top: water level of Lake Athabasca at Ft. Chipewyam. Middle: annual (water year) flow of Peace River at Peace River. Bottom: annual (water year) flow of Athabasca River at Athabasca. Horizontal lines mark long-term means of reconstructed series.

**Table 8**. Summary of single-year extremes[1] of water level and streamflow.

| Rank[2] | Lake Level[3] (m) | Streamflow[4] ($m^3$/sec) Peace R. | Athabasca R. |
|---|---|---|---|
| **L** | **208.47 (1945)** | **1024.0 (1969)** | **293.5 (1919)** |
| 1 | 208.73 (1982) | 1224.3 (1869) | 296.7 (1847) |
| 2 | 208.83 (1945) | 1312.9 (1946) | 310.9 (1852) |
| 3 | 208.87 (1943) | 1424.9 (1886) | 323.0 (1940) |
| 4 | 208.92 (1886) | 1433.6 (1982) | 323.0 (1859) |
| 5 | 208.93 (1885) | 1437.2 (1941) | 327.6 (1936) |
| 6 | 208.95 (1980) | 1444.5 (1945) | 334.9 (1851) |
| 7 | 208.96 (1946) | 1450.2 (1953) | 335.2 (1941) |
| 8 | 208.99 (1893) | 1468.3 (1939) | 339.0 (1919) |
| 9 | 209.00 (1890) | 1474.0 (1970) | 345.2 (1933) |
| 10 | 209.01 (1892) | 1480.1 (1929) | 350.6 (1922) |
| **H** | **211.33 (1935)** | **2782.9 (1996)** | **703.8 (1954)** |
| 1 | 210.37 (1965) | 2301.7 (1965) | 544.0 (1826) |
| 2 | 210.25 (1963) | 2263.5 (1964) | 543.0 (1836) |
| 3 | 210.16 (1964) | 2217.7 (1966) | 536.8 (1830) |
| 4 | 210.11 (1804) | 2196.7 (1963) | 519.4 (1829) |
| 5 | 210.10 (1932) | 2163.6 (1935) | 515.7 (1954) |
| 6 | 210.07 (1966) | 2087.1 (1958) | 515.5 (1991) |
| 7 | 210.05 (1959) | 2075.4 (1960) | 514.7 (1982) |
| 8 | 210.04 (1934) | 2050.9 (1875) | 513.0 (1827) |
| 9 | 210.04 (1935) | 2026.7 (1877) | 509.9 (1879) |
| 10 | 210.03 (1936) | 2021.1 (1805) | 507.9 (1881) |

[1]The single lowest value in the observed series is followed by the top 10 ranking low reconstructed values, and likewise for the highest values. The year in parentheses is the ending year for the running mean (e.g., 1945 refers to the period 1941-45).

[2]Ranks 1-10 under "L" are the lowest 10 reconstructed values. Ranks 1-10 under "H" are the highest 10.

[3]Water Level (above sea level) of Lake Athabasca at Ft. Chipewyan

[4]Annual total (water year, Oct 1-Sept 30) streamflow of Peace River at Peace River and Athabasca River at Athabasca

predictor tree-ring chronologies. The two series are not similar in all years. For example, the low Peace River flow in 1869 was not accompanied by particularly low reconstructed lake level, and the extended lake-level low in the 1880s is more accentuated than the corresponding low-flow period on the Peace River.

The Athabasca River series frequently has opposite-sign moisture anomalies from those in the other two reconstructions. Extended low flows on the Athabasca in the 1840s appear opposite slightly higher than normal flows on the Peace and exceptionally high water level in Lake Athabasca.

A listing of the lowest and highest ten reconstructed values for each reconstruction emphasizes the high frequency of exceptionally dry years in the 1940s and wet years in the 1960s on the Peace River and in the delta (Table 8). This period followed immediately on the heels of a very dry period in the late 1930s on the Athabasca River. The single-year extremes of the observed data are listed in the first row of Table 8. The observed extremes are more severe than the reconstructed extremes. This underestimation of extremes is a property of the regression method, and can only be mitigated by increasing the explanatory power of the regression.

**Smoothed variations**. The time series plots of annual reconstructions (Figure 12) contain many low-frequency features in the form of extended multi-year highs and lows and wavelike swings in moisture conditions lasting several decades. Spectra of the reconstructions corroborate the importance of the low-frequency variation (Figure 13). The reconstructions are characterized by low-frequency spectra, with much variance at wavelengths longer than 10 years (frequencies lower than 0.1 $year^{-1}$). The percentage of variance at wavelengths longer than 10 years as computed by the fractional area under the plotted spectra is 77% for Lake Athabasca water level, 59% for Peace River streamflow and 50% for Athabasca streamflow. In contrast, a white noise series would be expected to have only about 20% of the variance at those low frequencies. Each spectra in Figure 13 has a major peak at the low frequencies. These spectral peaks should not be interpreted physically, as they likely are artifacts of the detrending operation that converts ring widths to tree-ring indices. Detrending removes the lowest frequencies of variation and forces the spectrum of the resulting indices to dive as it approaches zero frequency. The major peaks in all three spectra in Figure 13 occur at the far left of the spectra, adjacent to the dive, and probably appear as peaks because variance at longer wavelengths has been processed out of the data. Disregarding those peaks, the spectra are concluded to show now evidence for regular cycles in the reconstructions.

Added importance may be attached to the low-frequency component of the tree-ring reconstruction because the reconstructions may actually be more accurate at low frequencies than high frequencies. The increased signal strength at low frequencies can be demonstrated for the Lake Athabasca water level reconstruction (Figure 14) . The correlation coefficient between observed and reconstructed water level for the unsmoothed data is $r$=0.60, increases to 0.84 when series are smoothed by a 10-year Gaussian filter, and continues to increase with greater smoothing.

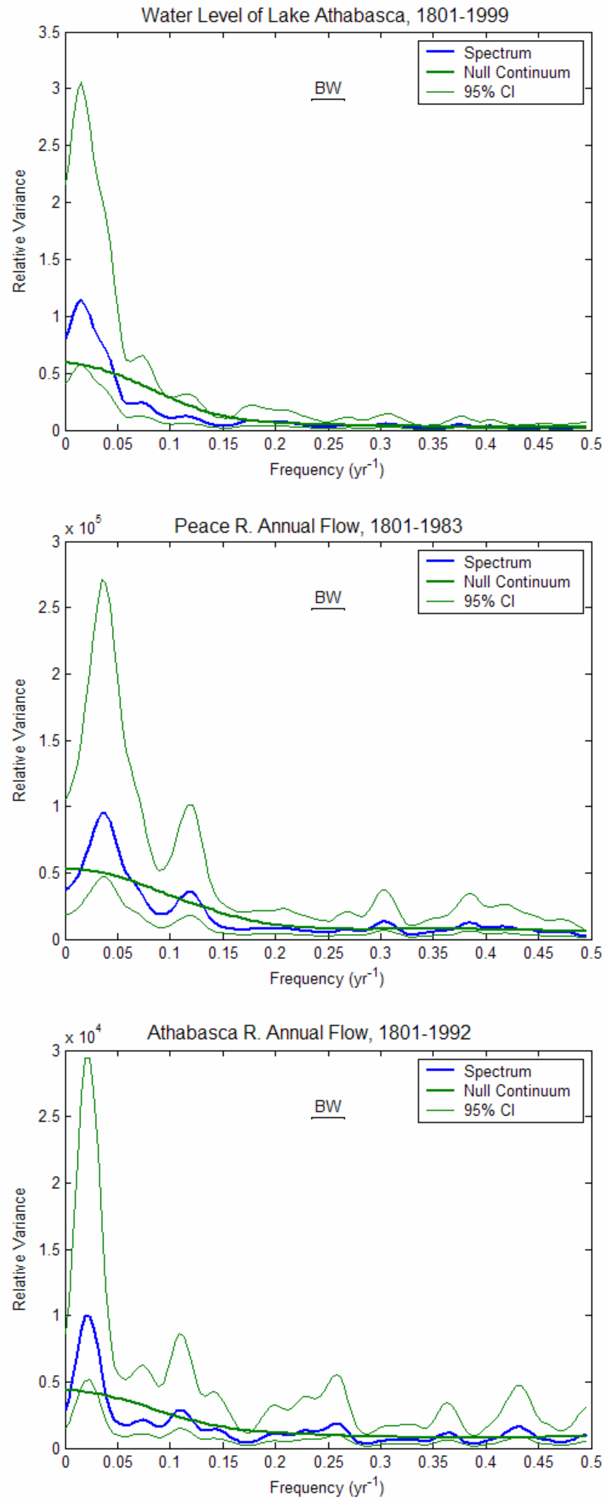



**Figure 13.** Sample spectra of reconstructed hydrologic series. Spectra computed by smoothed periodogram method (Bloomfield 2000). Successiive smoothing spans (Daniell filters) of length {5,7} used to smooth periodgram into spectal estimate. Spans {13,33,43} used to smooth periodogram into null continuum.

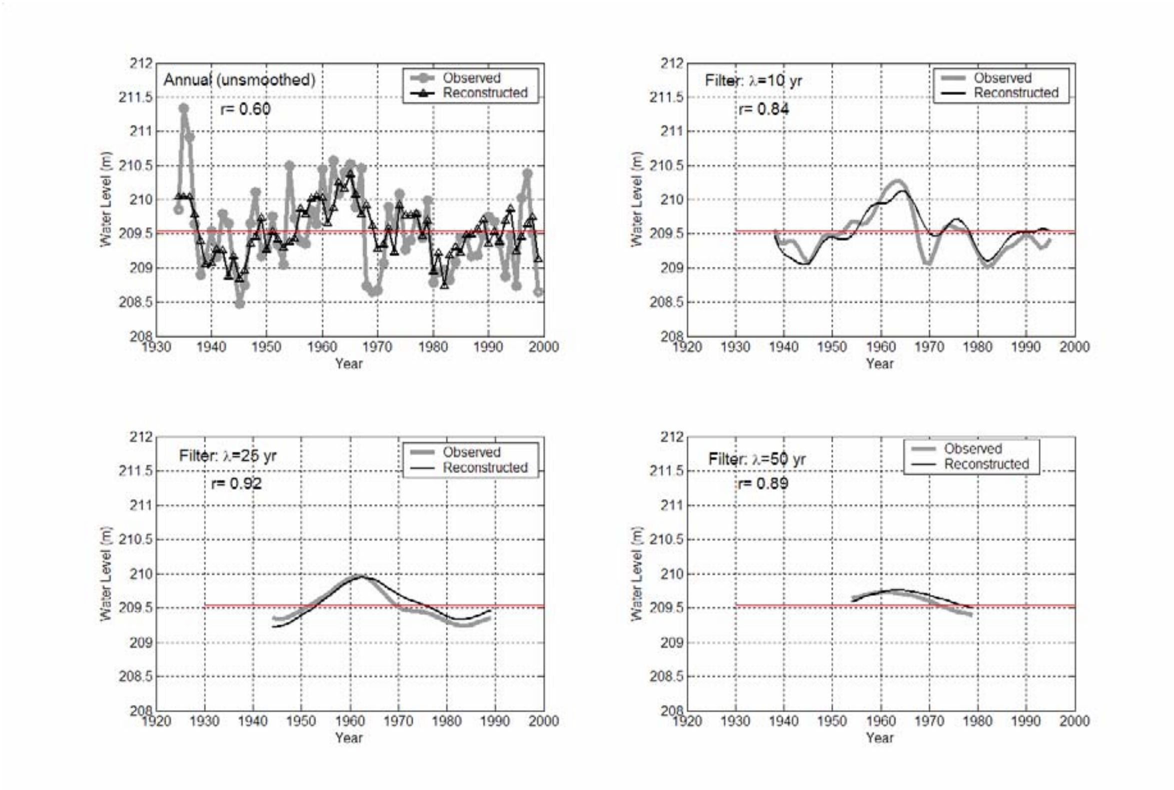



**Figure 14.** Time series plots illustrating increased accuracy of Lake Athabasca water level reonstruction at low frequencies. Plotted are the observed and reconstructed July 11-20 water levels for varying degrees of freedom. Degree of filtering and correlation coefficient between observed and reconstructed series are annotated. The weights for the Gaussian filters used (see "Methods") are listed in Appendix 6.

The three hydrologic reconstructions smoothed with a 10-year Gaussian filter are plotted in Figure 15. The Lake Athabasca water level series has three major lows: centered on 1888, 1944 and 1982. Lesser lows are centered on 1818 and 1917. The dominating high is centered on 1964. Lesser highest are centered on 1850 and 1934. A comparison of the reconstructed water level (Figure 15, Figure 12—top) with the time series plot of delta-mean tree-ring index (Figure 8) shows that the 1880s low is relatively more severe (say, compared with the 1940s low) in the reconstruction than in the mean tree-ring series. This amplification reflects the influence of the second predictor in the reconstruction model. The second predictor is PC#2 of the 8 delta chronologies, and represents a north/south contrast in growth anomalies across the delta. Low growth in the south, possibly reflecting reduced input of water from the Athabasca River thus pushes the reconstructed water level in the 1880s below that which would be inferred from simply averaging tree-growth across the delta.

The Peace River reconstruction has a major high near 1964 and major low near 1945. Other peaks and troughs are of much lower magnitude, but are generally in phase with the fluctuations in the Lake Athabasca water levels.

In contrast with the other reconstructions, the Athabasca River reconstruction has its major peaks and troughs before the 20$^{th}$ century. The major low is centered on 1851 and the major high on 1828. Lesser lows are centered on 1921 and 1940, lesser highs on 1836, 1874, and 1954. The Athabasca River series is sometimes in-phase (1870s to 1900) with the Lake Athabasca water level series and sometimes opposite phase (1840s and 1850s).

The fluctuations in smoothed reconstructions can also be summarized in terms of running means, or evenly-weighted averages over several years. The reconstructions contain some 3 to 4 times as many such periods for evaluation as the observed data (Table 9). The top 10 ranking running means for averaging lengths 5 and 10 years in each reconstruction are listed in Tables 10 and 11. The 5-year period ending in 1982 was the driest period for reconstructed lake level and 4$^{th}$ driest for Peace River flow. Note that the 1869 reconstructed Peace River flow was so low that the 5-year period ending in 1869 was also the driest 5-year period in that reconstruction. The 1840s and 1950s are prominent in the driest ranking of 5-year periods on the Athabasca River. The wettest reconstructed 5-year periods occur in the 1960s on Lake Athabasca and the Peace River and the 1830s on the Athabasca River.

For the 10-year running means (Table 11), the driest periods ended in the 1890s on Lake Athabasca, the late 1940s on the Peace River, and the 1850s on the Athabasca River. The wettest periods ended in the late 1960s both on Lake Athabasca and the Peace River, and in the 1830s on the Athabasca River. These rankings are consistent with the patterns of highs and lows in the 10-year Gaussian plot (Figure 15).

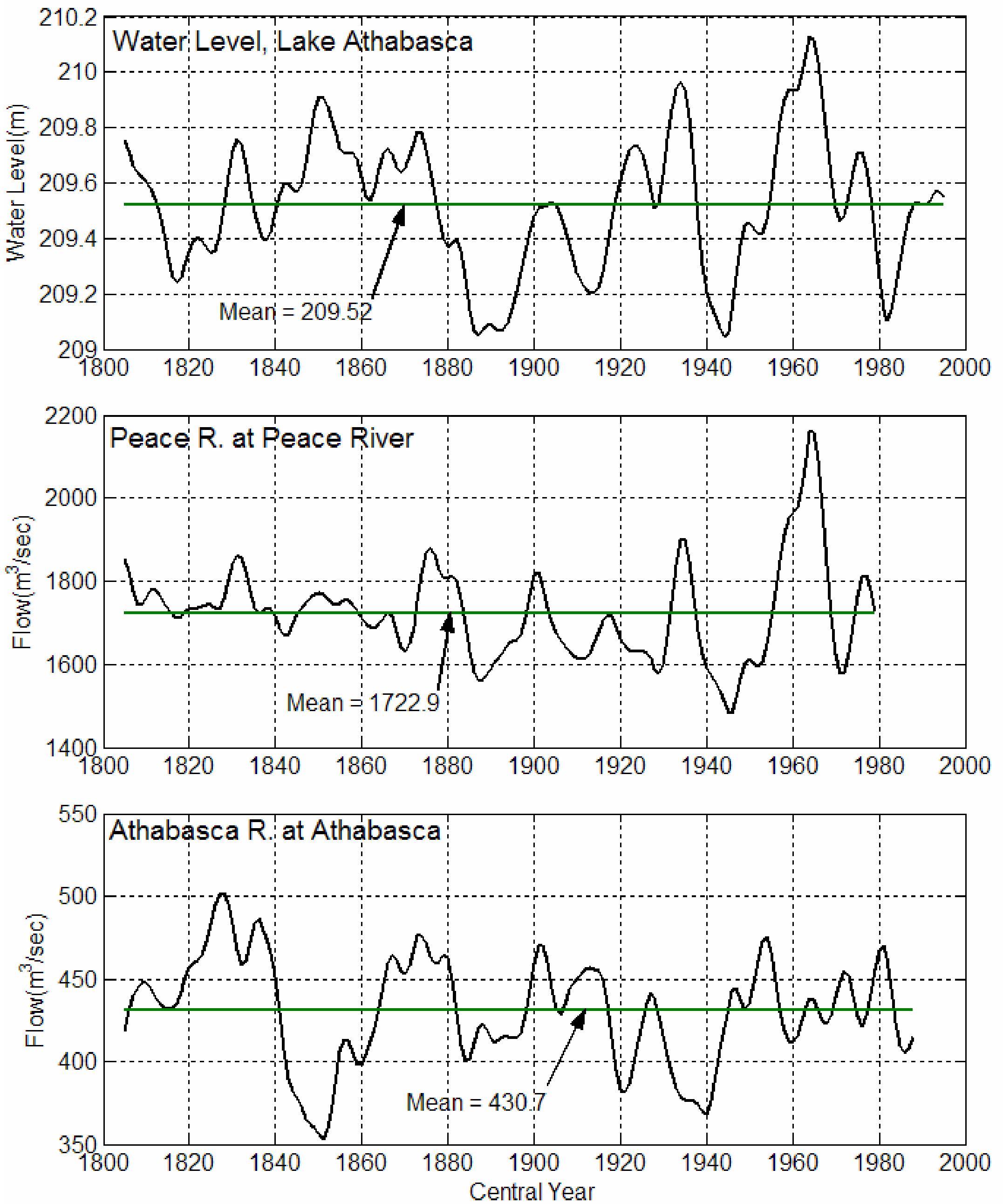



**Figure 15**. Time series plots of smoothed long-term hydrologic reconstructions. Series smoothed by 10-year Gaussian filter (filter weights listed in Appendix 6). Top: water level of Lake Athabasca at Ft. Chipewyam. Middle: annual (water year) flow of Peace River at Peace River. Bottom: annual (water year) flow of Athabasca River at Athabasca. Horizontal lines mark long-term means of annual reconstructed series (before smoothing).

**Table 9**. Number of running means available given time coverage of observed and reconstructed series

| Series[1] | Data Coverage[2] | Number of Running Means[3] 1-yr | 5-yr | 10-yr |
|---|---|---|---|---|
| **Lake Level** | | | | |
| Observed | 1934-1999 | 66 | 62 | 57 |
| Reconstructed | 1801-1999 | 199 | 195 | 190 |
| **Peace River** | | | | |
| Observed | 1916-31, 1959-2000 | 58 | 50 | 40 |
| Reconstructed | 1801-1983 | 183 | 179 | 174 |
| **Athabasca River** | | | | |
| Observed | 1915-30, 1952-2000 | 65 | 57 | 47 |
| Reconstructed | 1801-1992 | 192 | 188 | 183 |

[1]Water level of Lake Athabasca at Ft. Chipewyan (July 11-20 average), annual (water year) total streamflow of Peace River at Peace River, annual (water year) streamflow of Athabasca River at Athabasca

[2]Available period without missing data; not segmented records for the observed streamflow series

[3]Overlapping running means; an *n*-year running mean requires complete data for consecutive *n*-year period.

**Table 10**. Summary of most extreme 5-year running means[1] of water level and streamflow.

| Rank[2] | Lake Level[3] (m) | Streamflow[4] ($m^3$/sec) Peace R. | Athabasca R. |
|---|---|---|---|
| **L** | **208.47 (1945)** | **1024.0 (1969)** | **293.5 (1919)** |
| 1 | 208.73 (1982) | 1224.3 (1869) | 296.7 (1847) |
| 2 | 208.83 (1945) | 1312.9 (1946) | 310.9 (1852) |
| 3 | 208.87 (1943) | 1424.9 (1886) | 323.0 (1940) |
| 4 | 208.92 (1886) | 1433.6 (1982) | 323.0 (1859) |
| 5 | 208.93 (1885) | 1437.2 (1941) | 327.6 (1936) |
| 6 | 208.95 (1980) | 1444.5 (1945) | 334.9 (1851) |
| 7 | 208.96 (1946) | 1450.2 (1953) | 335.2 (1941) |
| 8 | 208.99 (1893) | 1468.3 (1939) | 339.0 (1919) |
| 9 | 209.00 (1890) | 1474.0 (1970) | 345.2 (1933) |
| 10 | 209.01 (1892) | 1480.1 (1929) | 350.6 (1922) |
| **H** | **211.33 (1935)** | **2782.9 (1996)** | **703.8 (1954)** |
| 1 | 210.37 (1965) | 2301.7 (1965) | 544.0 (1826) |
| 2 | 210.25 (1963) | 2263.5 (1964) | 543.0 (1836) |
| 3 | 210.16 (1964) | 2217.7 (1966) | 536.8 (1830) |
| 4 | 210.11 (1804) | 2196.7 (1963) | 519.4 (1829) |
| 5 | 210.10 (1932) | 2163.6 (1935) | 515.7 (1954) |
| 6 | 210.07 (1966) | 2087.1 (1958) | 515.5 (1991) |
| 7 | 210.05 (1959) | 2075.4 (1960) | 514.7 (1982) |
| 8 | 210.04 (1934) | 2050.9 (1875) | 513.0 (1827) |
| 9 | 210.04 (1935) | 2026.7 (1877) | 509.9 (1879) |
| 10 | 210.03 (1936) | 2021.1 (1805) | 507.9 (1881) |

[1]The single most extreme low 5-year running mean in the observed series is followed by the top 10 ranking low reconstructed running running means, and likewise for the highest running means. The year in parentheses is the ending year for the running mean (e.g., 1945 refers to the period 1941-45).

[2]Ranks 1-10 under "L" are the lowest 10 reconstructed running means. Ranks 1-10 under "H" are the highest 10.

[3]Water Level (above sea level) of Lake Athabasca at Ft. Chipewyan

[4]Annual total (water year, Oct 1-Sept 30) streamflow of Peace River at Peace River and Athabasca River at Athabasca.

**Table 11.** Summary of most extreme 10-year running means[1] of water level and streamflow.

| Rank[2] | Lake Level[3] (m) | Streamflow[4] ($m^3$/sec) Peace R. | Athabasca R. |
|---|---|---|---|
| **L** | **209.13 (1989)** | **1542.1 (1931)** | **394.6 (1964)** |
| 1 | 209.04 (1894) | 1528.7 (1948) | 360.7 (1852) |
| 2 | 209.06 (1895) | 1529.5 (1947) | 362.7 (1853) |
| 3 | 209.06 (1893) | 1540.3 (1950) | 367.0 (1855) |
| 4 | 209.09 (1896) | 1540.5 (1953) | 367.9 (1851) |
| 5 | 209.12 (1897) | 1547.4 (1949) | 368.0 (1854) |
| 6 | 209.12 (1892) | 1551.6 (1952) | 368.8 (1856) |
| 7 | 209.12 (1947) | 1554.1 (1946) | 371.6 (1941) |
| 8 | 209.13 (1948) | 1555.2 (1951) | 371.8 (1942) |
| 9 | 209.14 (1898) | 1555.3 (1954) | 376.7 (1940) |
| 10 | 209.17 (1946) | 1585.7 (1955) | 377.6 (1850) |
| **H** | **210.17 (1967)** | **1975.1 (1997)** | **495.0 (1980)** |
| 1 | 210.02 (1966) | 2069.7 (1967) | 489.1 (1830) |
| 2 | 210.02 (1967) | 2053.9 (1966) | 485.0 (1835) |
| 3 | 210.01 (1968) | 2041.0 (1968) | 484.9 (1836) |
| 4 | 210.00 (1965) | 2020.7 (1969) | 482.8 (1832) |
| 5 | 209.97 (1969) | 2003.3 (1965) | 482.6 (1831) |
| 6 | 209.91 (1964) | 1960.5 (1970) | 480.6 (1834) |
| 7 | 209.90 (1970) | 1948.0 (1964) | 478.9 (1833) |
| 8 | 209.86 (1971) | 1928.0 (1971) | 478.9 (1829) |
| 9 | 209.84 (1972) | 1900.5 (1972) | 478.5 (1838) |
| 10 | 209.83 (1856) | 1892.5 (1963) | 478.0 (1837) |

[1]The single most extreme low running mean in the observed series is followed by the top 10 ranking low reconstructed running means, and likewise for the highest running means. The year in parentheses is the ending year for the running mean (e.g., 1945 refers to the period 1941-45).

[2]Ranks 1-10 under "L" are the lowest 10 reconstructed running means. Ranks 1-10 under "H" are the highest 10.

[3]Water Level (above sea level) of Lake Athabasca at Ft. Chipewyan

[4]Annual total (water year, Oct 1-Sept 30) streamflow of Peace River at Peace River and Athabasca River at Athabasca.

**Covariation of Peace River and Athabasca River.** The time series plots of reconstructions suggest a strong agreement of variations of Lake Athabasca water level and Peace River annual flow and a much weaker agreement of Lake Athabasca water level with the Athabasca River flow. Correlation coefficients between pairs of the three reconstructions are listed in Table 12. The correlation between reconstructed Lake Athabasca water level and Peace River flow ($r$=0.65) is highly significant. The remaining correlations are not significant. The lack of correlation between the two annual flow series (Peace R. and Athbabasca R.) is surprising, as the observed annual series are significantly correlated ($r$=0.37, $p$-value<0.01) for the 57 years of overlap in the interval 1916-1999. The two reconstructed series also are not significantly correlated over roughly the available data between 1916 and 1992. Thus the reconstructions do not reproduce the observed positive relationship between the Peace and Athabasca River annual flows in the current century. This failure may simply result from the low $R^2$ values for the reconstructions: the spatial linkage may be lost in the unexplained variance of the reconstructions.

A sliding-correlation analyis of the two reconstructed river flows using a 33-year window essentially also indicates no significant correlation (Figure 16). In this analysis, the null hypothesis is the so-called "universal" null hypothesis: that all of the evaluated correlations are zero. Results show that this hypothesis cannot be rejected at the 0.05 level. The direction of change in correlation over time is consistent with major features in the plotted time series (Figure 12 and Figure 16, top). For example, the correlation rises during the period of in-phase behavior of the two series centered on the 1880s.

**Competing models and alternative model structures.** The modeling procedure used to generate the reconstructions here was conservative, with care taken not to overfit the model with too many predictors, or to restrict the calibration period to years with strong correlation between series. Exploratory reconstructions were run to test the sensitivity of results to less stringent controls.

Varying the calibration period makes a huge difference to the model statistics for these reconstructions. For example, if the calibration period for the Athabasca River reconstruction model is specified to end in 1965 instead of 1992, a fairly simple model with just three predictors accounts for 62% of the calibration flow variance, compared with 25% of the variance for the model based on the longer calibration period. The longer calibration period was used in this study to avoid spurious relationships, which frequently arise when models are fit to very short sample sizes. This is especially important for these reconstructions because the climatic regime for western North America is known to shift on decadal time scales (Timoney et al. 1997).

Increasing the number of predictors can also result in models with misleadingly high accuracy. For example a reconstruction model for lake Athabasca water level with all 8 delta tree-ring PCs, lags 0, +1 (16 variables) in the predictor pool, 12 predictors chosen

**Table 12**. Correlation[1] matrix of reconstructed hydrologic series[2]

| | WL | Peace | Athab. |
|---|---|---|---|
| Water Level | 1.00 | 0.65** (183) | -0.21 (192) |
| Peace R. | | 1.00 | -0.01 (183) |
| Athabasca R. | | | 1.00 |

[1]Product-moment correlations between pairs of series based on all available in years of overlapping data. Number of observations (years of overlap) in parentheses below correlation coefficient. Correlations significantly different from zero at alpha-level of 0.01 marked by "**"

[2]WL=water level of Lake Athabasca at Ft. Chipewyan; Peace=annual (water-year) flow of Peace River at Peace River; Athab.=annual (water-year) flow of Athabasca at Athabasca

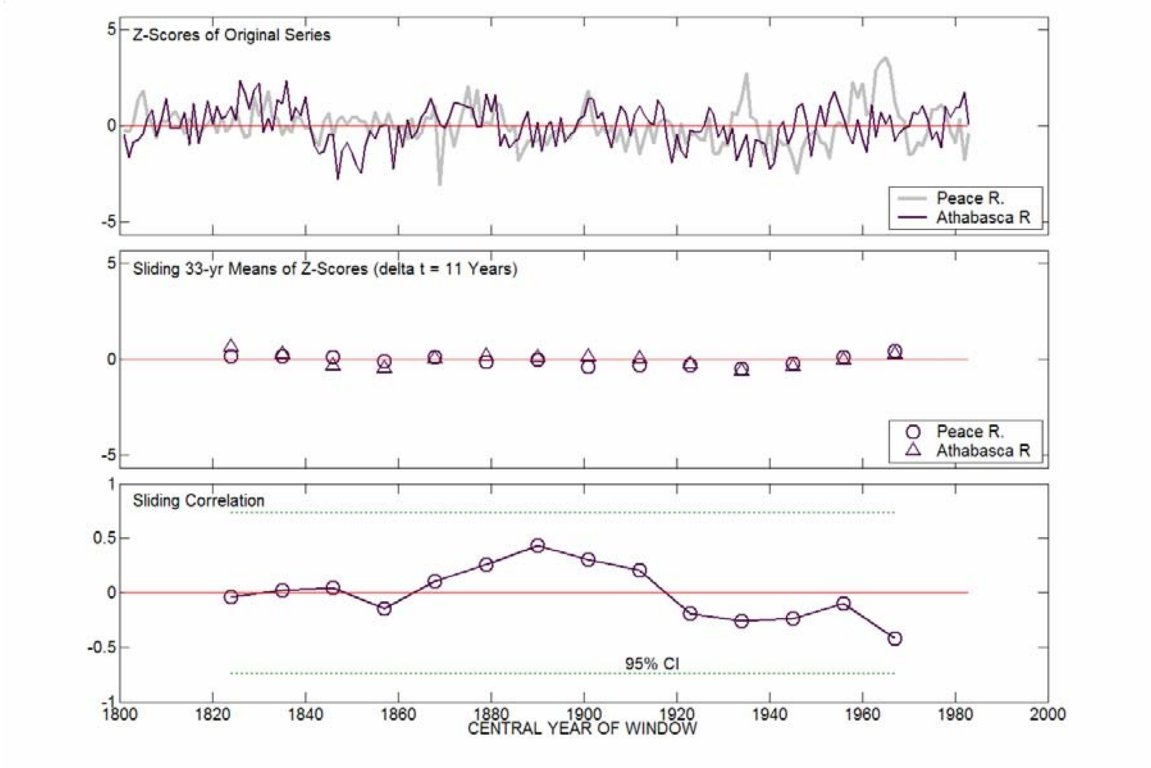



**Figure 16.** Sliding-correlation analysis of reconstructed flows of Peace River and Athabasca River. Means and correlations are computed in a sliding 33-year window. Top: annual reconstructed values of streamflow, 1801-1983, as Z-scores (mean 0, standard deviation 1) to adjust for scale differences. Middle: sub-period means of z-score reconstructions for 33-year periods offset by 11 years. Bottom: correlation coefficient between reconstructed flows on the two rivers for the 33-year periods. The 95% confidence interval for the correlations has been adjusted (widened) to account for the simultaneous evaluation of multiple sample correlations (Bonferroni adjustment), and the reduction of effective sample size due to autocorrelation in the individual series. The confidence interval is applicable to a two-tailed test of the universal null hypothesis that all of the sample correlations are zero against the alternative hypothesis that one or more of the correlations is different than zero.

by forward stepwise regression, and a calibration period 1935-67 accounted for more than 75% of the calibration period variance of observed water level. The model had a negative RE statistic, however, indicating no skill on independent data! The accuracy in this case is clearly a combination of overfitting (too many variables in pool of potential predictors as well as in the final model), and use of a calibration period for which the correlation between tree-rings and water level is relatively high compared with the full (1935-99) period of available data.

Overfitting of the reconstruction model by Stockton and Fritts (1973) is probably the explanation for the lack of correlation between the new Lake Athabasca water level reconstruction model presented here (Figure 12, top) and the corresponding reconstruction by Stockton and Fritts (1973), which was based on a short calibration period (1935-67), a complicated regression model (canonical regression with 12 predictors) and was not checked for accuracy on independent data (e.g., no quantitative validation). The two reconstructions plotted together in Appendix 7 track one another in the calibration period but diverge radically in earlier periods.

### *5.6 Stable-Isotope Analysis*

**Sample subdivision.** Four tree-ring core samples from site QFS (Figure 3, Table 1) were analyzed for stable isotopes of carbon ($\delta^{13}$ C) and oxygen ($\delta^{18}$ O) in wood cellulose (see "Methods"). Site QFS was chosen for this analysis because it is centrally located in the delta tree-ring collections and its ring-width chronology is highly correlated ($r$>0.50) with the other 7 delta chronologies (Figure 5). Moreover, the spread-out sampling scheme (boat collection) at QFS allows for relatively wide spacing (>1 km) of sampled trees.

Cost constraints dictated that a maximum of about 100 individual samples could be analyzed in this study. To check the consistency of isotopic variations from tree-to-tree and test for relationships between isotope records and hydroclimatic variables, groups of rings for the most recent period, 1940-2001, were separated for extraction of the cellulose and measurement of isotopes (see "Methods"). To allow sufficient wood for each sample, groups of 2-4 rings were analyzed as individual samples. The year groupings are as follows:

1879-1881- reported low delta water levels in historical records (Wuetherick 1972)
1888-1890- low tree growth and reconstructed water level (Figure 15, top)
1940-1941
1942-1944
1945-1947
1948-1950
1951-1953
1954-1956
1957-1959
1960-1962
1963-1964
1965-1967

1968-1971- period of filling of dam; very low lake level
1972-1974
1975-1977
1978-1980
1981-1983
1984-1986
1987-1989
1990-1992
1993-1995
1996-1998
1999-2001

This stratification includes ten periods before and after the building of Bennett Dam, one period coinciding with the filling of the dam, and two earlier periods of historical hydrologic interest.

**<u>Measurements and laboratory measurement error</u>**. Values of $\delta^{13}C$ and $\delta^{18}O$ for the year-groups of individual cores are listed in Table 13. The standard deviation of $\delta^{13}C$ measurements variations over time (from year-group to year-group) for individual cores is large compared with laboratory measurement error. For example, the smallest standard deviation for any column of $\delta^{13}C$ data in Table 13 is 0.62 ‰, while the measurement error reported by the laboratory is 0.04 ‰ for repeated analysis of an organic standard.

Measurements are more uncertain for $\delta^{18}O$: measurement error reported by the lab is 0.40 for repeated measure of an organic standard, while the standard deviations of the measurements for the four cores range from 0.65 ‰ to 1.42 ‰.

**<u>Tree-to-tree consistency of isotopic variations</u>.** Time series plots of $\delta^{13}C$ for the sampled trees are shown in Figures 17a . Little parallel behavior is evident in these plotes. $\delta^{13}C$ rises sharply in 3 of 4 trees in the 1951 group and drops sharply in all 4 trees in the 1957 group. More often, however, $\delta^{13}C$ for one or more trees deviates greatly from the others. A scatterplot matrix (not shown) indicated a nonexistent, or barely perceptible weak positive, relationship in $\delta^{13}C$ variations between trees. Only for pair QFS08B/QFS01A did correlation reach significance at the 0.05 level.

The time series plots for $\delta^{18}O$ suggest generally stronger between-tree agreement than for $\delta^{13}C$, but the picture is clouded by the extremely anomalous behavior of QFS08B. Correlation reaches significance at the $\alpha$=0.01 level for pair QFS01A/QFS05A. If core QFS08B is disregarded, correlations for remaining pairs are all positive and greater than 0.42. The time series plots of isotope ratios show now consistent anomalous behavior for the sample representing the filling period of Bennett Dam, and if fact differences between trees are relatively large then. The listed isotope ratios in Table 13 are also not unusual during the two sample periods (1879-81, 188-90) selected for their known lake-level anomalies.

**Table 13.** Stable isotope measurements[1] for selected cores[2] from site QFS

| | | $\delta^{13}C$ (°/∘∘) | | | | $\delta^{18}O$ (°/∘∘) | | | |
|---|---|---|---|---|---|---|---|---|---|
| **YEARS**[3] | **N**[4] | **01A** | **05A** | **08B** | **10A** | **01A** | **05A** | **08B** | **10A** |
| 1879-1881 | 3 | -22.2 | -22.1 | -22.6 | -23.6 | NaN[5] | 22.5 | NaN | 22.4 |
| 1888-1890 | 3 | -22.9 | -23.1 | -22.5 | -24.1 | NaN | 22.6 | NaN | 21.4 |
| 1940-1941 | 2 | -22.1 | -24.0 | -22.4 | -23.4 | 22.3 | 23.2 | 23.0 | 22.9 |
| 1942-1944 | 3 | -21.6 | -22.6 | -22.2 | -22.9 | 22.5 | 23.3 | 27.7 | 22.0 |
| 1945-1947 | 3 | -22.2 | -22.4 | -22.0 | -22.9 | 21.1 | 21.7 | 26.5 | 21.3 |
| 1948-1950 | 3 | -22.1 | -23.1 | -21.4 | -22.5 | 21.3 | 21.6 | 26.5 | 21.6 |
| 1951-1953 | 3 | -20.9 | -21.4 | -22.2 | -21.3 | 21.9 | 23.1 | 25.4 | 22.7 |
| 1954-1956 | 3 | -22.3 | -22.1 | -21.6 | -22.0 | 22.6 | 23.8 | 25.0 | 22.3 |
| 1957-1959 | 3 | -22.8 | -23.7 | -22.4 | -24.4 | 22.0 | 22.0 | 24.2 | 22.8 |
| 1960-1962 | 3 | -23.3 | -22.8 | -23.0 | -22.7 | 22.0 | 23.1 | 25.3 | 21.3 |
| 1963-1964 | 2 | -23.5 | -22.8 | -24.2 | -22.9 | 21.5 | 23.0 | 25.7 | 21.8 |
| 1965-1967 | 3 | -23.2 | -24.0 | -22.7 | -22.3 | 21.0 | 21.7 | 21.9 | 22.7 |
| 1968-1971 | 4 | -22.3 | -24.5 | -22.0 | -23.4 | 21.8 | 22.6 | 25.3 | 21.7 |
| 1972-1974 | 3 | -22.5 | -23.3 | -21.9 | -22.8 | 20.9 | 22.6 | 23.2 | 19.9 |
| 1975-1977 | 3 | -22.7 | -23.8 | -22.5 | -22.3 | 21.2 | 22.0 | 25.8 | 21.1 |
| 1978-1980 | 3 | -22.3 | -24.2 | -22.1 | -22.8 | 20.5 | 22.6 | 25.6 | 20.8 |
| 1981-1983 | 3 | -21.6 | -23.1 | -21.4 | -21.8 | 20.8 | 20.3 | 24.4 | 20.0 |
| 1984-1986 | 3 | -23.5 | -23.6 | -21.8 | -22.5 | 22.0 | 22.5 | 24.1 | 22.4 |
| 1987-1989 | 3 | -22.5 | -22.2 | -22.8 | -22.6 | 21.9 | 23.4 | 24.4 | 22.4 |
| 1990-1992 | 3 | -23.5 | -25.1 | -22.3 | -22.1 | 20.6 | 22.2 | 24.1 | 22.0 |
| 1993-1995 | 3 | -22.5 | -23.0 | -21.6 | -21.9 | 22.2 | 23.2 | 23.3 | 23.0 |
| 1996-1998 | 3 | -22.7 | -23.9 | -23.1 | -22.8 | 21.4 | 21.4 | 23.5 | 21.6 |
| 1999-2001 | 3 | -21.5 | -23.7 | -22.3 | -23.1 | 20.6 | 21.4 | 23.0 | 22.1 |

[1]Measurements in units of "per mil"
[2]Cores labeled by tree and core(e.g.,**01A** is core A from tree #1)
[3]Years in the group of rings
[4]Number of years in year group (varies from 2 to 4)
[5]Missing data indicated by "not a number" (NaN) symbol. These missing values result from insufficient wood for both carbon and oxygen isotope measurements for the year-groups in the 1800s.

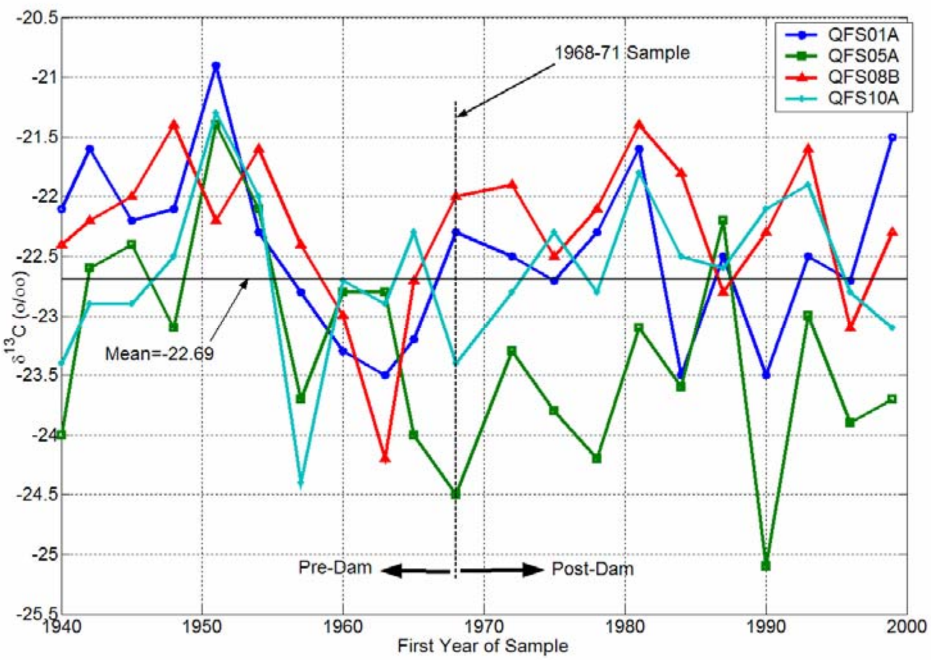



**Figure 17a**. Time series plots $\delta^{13}C$ of cellulose from groups of rings from four trees from site QFS. Number of rings in samples range from two to four. Sample for 1968-71 represents time of filling of W. A.C. Bennett Dam.

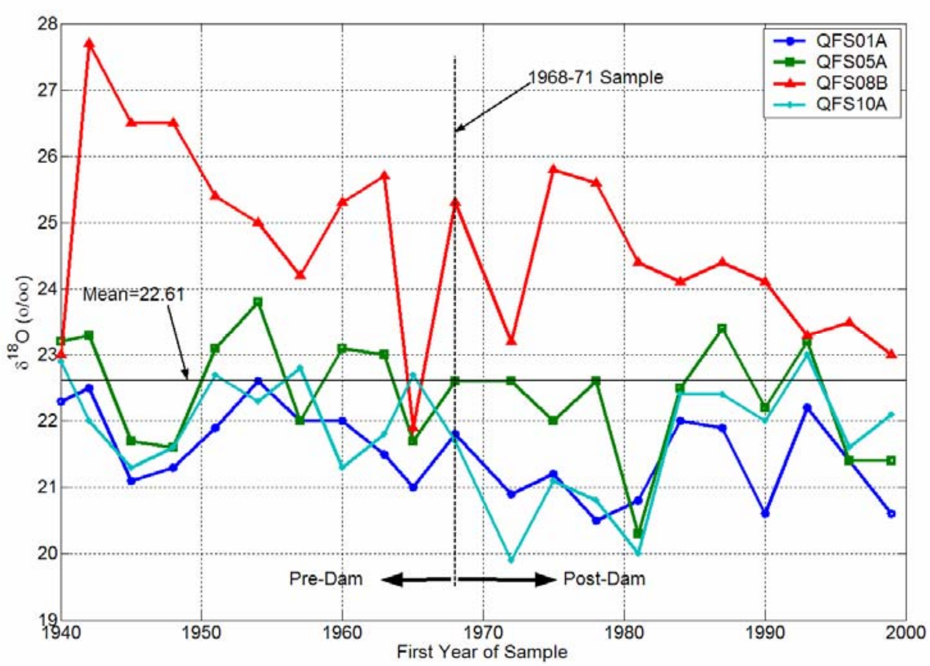



**Figure 17b**. Time series plots $\delta^{18}O$ of cellulose from groups of rings from four trees from site QFS. Remainder of legend as in Figure 17a.

Although correlations between some trees are significant positive, tree-to-tree variability in $\delta^{13}C$ and $\delta^{18}O$ is large. This variability limits the usefulness of the $\delta^{13}C$ and $\delta^{18}O$ series as proxy for studying large-scale environmental phenomena and indeed limits the ability to identify the driving environmental signals. The expressed population signal (EPS) (see "Methods") was used to evaluate the adequacy of the sample size (number of trees) for capturing the unknown site signal for isotope ratios. The mean between-tree correlations and required sample sizes for an EPS of 0.85 are as follows:

$\delta^{13}C: \bar{r} = 0.25, \quad N_{crit} = 17$ trees

$\delta^{18}O: \bar{r} = 0.36, \quad N_{crit} = 10$ trees

It is clear from this analysis that the sample size of one core from each of 4 trees would need to be expanded by a factor of perhaps 5 (to ~20 trees) to capture a reasonably representative signal of site-wide $\delta^{13}C$ and $\delta^{18}O$ variations.

**Correlation with hydrologic, climatic and ring-width series.** Correlations with $\delta^{13}C$ and $\delta^{18}O$ of individual cores were computed for six different environmental variables. Each of these variables was averaged over the 2-4 year period coinciding with the year-groupings for isotope analysis. The variables and some of the plausible relationships that might induce correlation are:

July 11-20 mean lake level of Lake Athabasca at Ft. Chipewyan. Low water level might be associated with drought stress through increased stomatal closure, less discrimination against $^{13}C$ in assimilating carbon, and elevated $\delta^{13}C$ in the cellulose (negative correlation between water level and $\delta^{13}C$).

Ring-width index for site QFS (standard chronology). Drought stress might be associated with narrow rings and also with elevated $\delta^{13}C$. Thus narrow rings are expected to go with elevated $\delta^{13}C$ (negative correlation between ring-width index and $\delta^{13}C$) .

Total annual (water-year) precipitation measured at Ft. Chipewyan. Low water-year precipitation leads to low soil moisture, water stress in trees, and elevated $\delta^{13}C$ (negative correlation between annual precipitation and $\delta^{13}C$).

Percentage of water-year precipitation falling in the warm-season months June-September. Water for growth derived proportionally more from water with higher $\delta^{18}O$ (positive correlation between percentage of annual precipitation in the summer months and $\delta^{18}O$).

Maximum daily snow depth in the first two weeks of April recorded at Ft. Chipewyan. Cold season precipitation and snowmelt is relatively low in $\delta^{18}O$. Higher snow depth leads to greater use of cool-season moisture in ring cellulose (negative correlation between snow depth and $\delta^{18}O$).

<u>Mean warm-season (June-Sept) temperature (from daily means) at Ft. Chipewyan</u>. Previous studies have demonstrated a high positive correlation of temperature and $\delta^{18}O$ of cellulose in white spruce from Alberta, Canada (Gray and Thompson 1967). A drought effect might also be reasonable – hot summers being dry and associated with drought stress and elevated $\delta^{13}C$ (positive correlation between summer temperature and $\delta^{18}O$, positive correlation between summer temperature and $\delta^{13}C$).

Computed correlations are listed in Table 14. Correlations are shown for the individual trees and for the 4-tree ($\delta^{13}C$) or 3-tree ($\delta^{18}O$) average. Tree QFS8B was omitted from the $\delta^{18}O$ average because of its clearly anomalous behavior (Figure 17b). The sample size (number of year-groups) for some of the correlations is too low to be of much practical use. Sample size varies from 4 for the two precipitation variables to 20 for the ring-width and lake-level variables. The correlation results show no strong evidence for possible causative factors for the isotopic variations. Only 4 of the 48 correlation coefficients are significant at the 0.05 level. The only relationship with the same sign of correlation for all four trees is $\delta^{13}C$ vs ring-width index, for which the correlation is negative, and weakly significant (.05 level) for two trees. The same two trees have weakly significant negative correlations with lake level. The sign of that correlation is consistent with the expected relationship between drought stress and $\delta^{13}C$.

The highest correlations for the $\delta^{18}O$ variable are negative with the percentage of water-year precipitation falling in the months June-Sept. Disregarding tree QFS08B, which appears to wander from the others (Figure 17b), the correlations are -0.92, -0.74 and -.85. The direction of relationship is opposite that expected from past experience. It should be stressed, however, that only four year-groups are available for this analysis, and that the correlations, though high, are not significant for such a small sample size. Moreover, the range of the climatic variable was extremely small in the four observations: percentage of precipitation falling in summer varied only between 50% and 54% for those 4 year-groups. .

Averaging isotope series over trees has the effect of slightly raising the absolute magnitude of correlations between $\delta^{13}C$ and ring-width index and between $\delta^{18}O$ and the percentage of annual precipitation falling in summer (bottom of Table 14). The correlation of -0.94 between $\delta^{18}O$ and the percentage of annual precipitation falling in summer is of course based on too few values (4) to assess significance.

**Table 14.** Product-moment correlations of $\delta^{13}C$ and $\delta^{18}O$ with hydrologic, climatic and ring-width variables. Significance at $\alpha-$level 0.05 (two-tailed test) marked by asterisk.

| SAMPLE[1] | Lake[2] | Tree[3] | PPT[4] | Pctg[5] | Snow[6] | T[7] |
|---|---|---|---|---|---|---|
| 1 qfs01a C13 | -0.51(20)* | -0.65(20)* | +0.35(4) | +0.40(4) | +0.10(6) | +0.12(8) |
| 2 qfs05a C13 | +0.01(20) | -0.33(20) | -0.04(4) | -0.61(4) | +0.46(6) | +0.35(8) |
| 3 qfs08b C13 | -0.62(20)* | -0.67(20)* | +0.54(4) | +0.10(4) | +0.11(6) | -0.43(8) |
| 4 qfs10a C13 | -0.04(20) | -0.34(20) | -0.84(4) | +0.15(4) | -0.40(6) | +0.63(8) |
| 5 qfs01a O18 | -0.02(20) | -0.10(20) | -0.67(4) | -0.92(4) | +0.50(6) | -0.07(8) |
| 6 qfs05a O18 | +0.15(20) | -0.02(20) | +0.02(4) | -0.74(4) | +0.25(6) | -0.19(8) |
| 7 qfs08b O18 | -0.21(20) | -0.32(20) | -0.80(4) | +0.26(4) | -0.48(6) | +0.10(8) |
| 8 qfs10a O18 | +0.04(20) | +0.07(20) | -0.80(4) | -0.85(4) | -0.39(6) | +0.24(8) |
| 9 Mean C13 | -0.39(20) | -0.69(20)* | +0.35(4) | -0.26(4) | +0.12(6) | +0.33(8) |
| 10 Mean O18 | +0.07(20) | -0.01(20) | -0.64(4) | -0.94(4) | +0.08(6) | +0.02(8) |

[1]Series 1-8 are individual cores: C13 = $\delta^{13}C$, O18 = $\delta^{18}O$. Series 9 is the mean $\delta^{13}C$ series. Series 10 is the mean $\delta^{18}O$ series, an average over 3 trees (outlier 08B omitted).
[2]10-day mean (July 11-20) water level of Lake Athabasca at Ft Chipewyan
[3]Ring-width index for tree-ring chronology QFS
[4]Total precipitation (water year) at Ft. Chipewyan
[5]Percentage of water-year precipitation falling in months June-September
[6]Maximim snow depth in first two weeks of April at Ft. Chipewyan
[7]Mean temperature, June-Sept, at Ft. Chipewyan

## *5.7 Dendroclimatic Changes With Bennett Dam*

Statistical tests were conducted for significance of the difference in water levels and tree-ring variables before and after construction of Bennett Dam. Post-dam statistics of reconstructed water level were also placed in a long term context by comparison with statistics for all availble reconstruction sub-samples the same size as the 28-year post-dam period.

**Tree-growth pre-dam vs post-dam.** The difference between water levels before and after filling of Bennett Dam was tested for significance using a Wilcoxon rank-sum test (see "Methods"). Separate tests were run for the observed water levels and the reconstructed water levels. The data distributions for sub-periods 1935-67 and 1972-99 in the observed and reconstructed data are summarized graphically in the box plots of Figure 18. An additional box plot is included for the long-term pre-dam period (1801-1967) for the reconstructed data.

For the observed data, changes from pre-dam to post-dam are as follows: lower median (209.65m to 209.44m), lower high extremes, and more negative skew in the middle of the distribution (lower part of box stretched out relative to upper part).

The reconstructed data show these same qualitative differences from 1935-67 to 1972-99. Note the y-scale is compressed in the reconstruction as a result of the conservative property of regression estimates. For the reconstructed data, the median drops from 209.53m to 209.48m.

The box plot for the 1801-1967 reconstructed data is similar to that for the 1935-67 reconstructed data, and in fact the two medians are the same (209.53 m).

The boxplots for the observed and reconstructed data suggest a decline in water level pre-dam to post-dam. Statistical significance of the decline was tested by the rank-sum test. The null hypothesis is that the samples before and after the construction of the dam come from the same distribution. Test results are as follows:

Observed data: 1935-67 to 1972-99
Rank sum = 727
p-value = 0.04
Reject null hypothesis

Reconstructed data: 1935-67 to 1972-99
Rank sum = 785
p-value = 0.23
Cannot reject null hypothesis

y

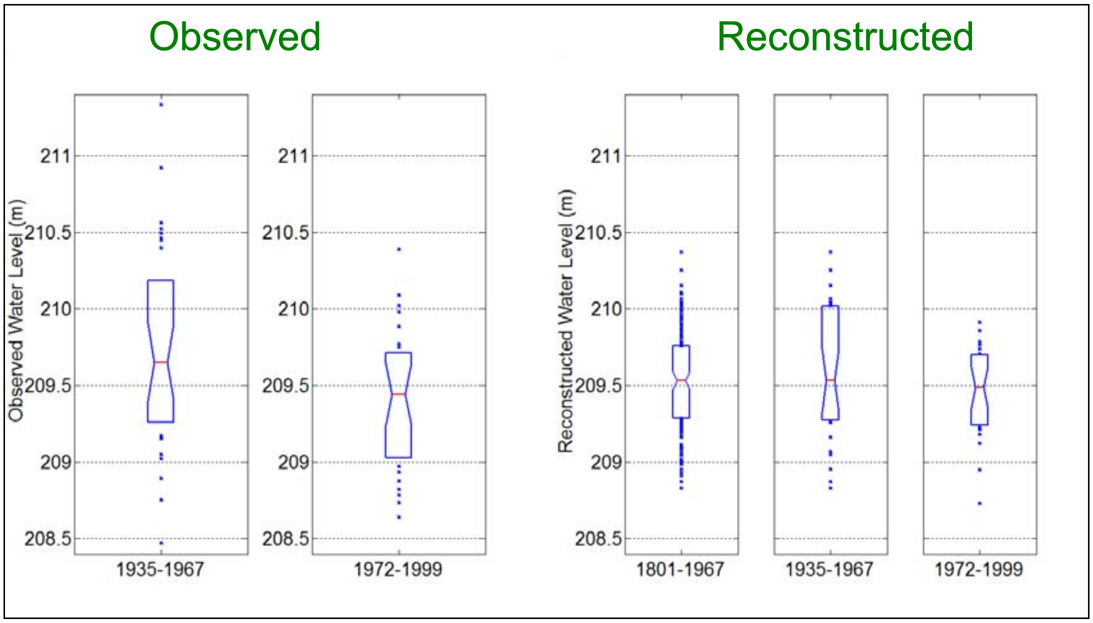



**Figure 18**. Box plots comparing water levels of Lake Athabasca before and after construction of W.A.C. Bennett Dam. Two box plots at left are based on observed water level. Three box plots at right are based on tree-ring reconstruction. Box elements as follows: horizontal line = median; top of box = upper limit of third quartile; bottom of box = lower limit of second quartile quartile; points = values following outside second and third quartiles.

Reconstructed data: 1801-1967 to 1972-99
Rank sum = 2541
p-value = 0.46
Cannot reject null hypothesis

The observed data therefore support an alternative hypothesis that the water level samples pre-dam and post-dam come from different distributions. The reconstruction for the same sub-periods does not show a significant change. The reconstruction using the longer pre-dam period also does not show a significant decline. The direction of change of the *p*-values for the two tests on the reconstructed data suggest that were longer observed series available the drop in water –level pre-dam to post-dam might not be significant.

**Stable-isotope ratios pre-dam vs post-dam.** Separate Wilcoxon rank-sum tests were run for $\delta^{13}C$ and $\delta^{18}O$. The individual samples from the four cores were lumped for the analysis, resulting in 48 samples pre-dam (before 1968) and 40 samples post-dam (after 1971).

Let the pre-dam samples be A and the post-dam be B. The null hypothesis is that A and B are from the same population. The results of the test are listed below.

$\delta^{13}C$ results

> $N$ = 88 = total number of samples
> $N_a$ = 48 = number pre-dam
> $N_b$ = 40 = number post-dam
> Rank Sum = 1770.5
> $p$-value = 0.93981 →cannot reject null hypothesis

$\delta^{18}O$ results

> $N$ = 84 = total number of samples
> $N_a$ = 44 = number pre-dam
> $N_b$ = 40 = number post-dam
> Rank Sum = 1532.5
> $p$-value = 0.13449 →cannot reject null hypothesis

The pre-dam sample is slightly smaller for $\delta^{18}O$ because wood samples were not large enough to get $\delta^{18}O$ measurements on the two year groups before 1900 for two of the cores. Ranks sums for both tests were within the range expected by chance had the pre-dam and post-dam samples been drawn from the same population.

The Wilcoxon rank-sum tests described above was repeated by after averaging isotope ratios over cores. As in the correlation analysis, the isotope series were averaged over 4 trees for $\delta^{13}C$ trees and 3 trees for $\delta^{18}O$. Results are the same. The null hypothesis again cannot be rejected that the pre-dam and post-dam samples are from the same distribution cannot be rejected at the 0.05 alpha level.

**Tree-ring statistics in 28-year time-windows.** The purpose of this analysis was to quantify how anomalous the post-dam (1972-99) reconstructed water levels are in the context of the record back to A.D. 1801. The steps are as follows: 1) the 1801-1967 pre-dam Lake Athabasca water level reconstruction was segmented into overlapping periods the same length (28 years) as the 1972-99 post-dam period, 2) sample mean, standard deviation, range, and first order autocorrelation were computed for each sub-period, 3) the set of sample statistics was sorted and ranked to form an empirical cumulative distribution function (cdf), and 4) the empirical non-exceedance probabilities for 1972-99 statistics were interpolated from the cdf.

The 28-year sub-periods are overlapping, shifted by one year relative to one another. The available sub-periods are 1801-1828, 1802-1829, 1803-1830,…, 1940-1967. The total number of sub-periods is 140.

The resulting empirical cdf's and empirical non-exceedance probabilities are shown on the graphs in Figure 19. The monotonic-increasing line is the empirical cdf. The value of the statistic is read off the x-axis, and the non-exceedance probability off the y-axis. The arrows identify the value of the statistic for the 1972-1999 period and the non-exceedance probability of that value.

For example, for the standard deviation (lower left), the sample value computed for 1972-99 is 0.286. The 140 pre-dam standard deviations range from 0.194 to 0.437. The 1972-99 standard deviation is larger than 64% of the 140 sub-sample standard deviations, for a corresponding non-exceedance probability of 0.64. In other words, if a 28-year sub-sample is picked at random from the 140 samples in the long-term record, the probability of the 1972-99 standard deviation not being exceeded is 0.64.

The cdf's plotted in Figure 19 can similarly be used to place all four of the computed post-dam water level statistic in a long-term context. The cdf's indicate the following about the reconstructed water levels for the period 1972-99:

1. The mean is relatively low in a long-term context
2. The standard deviation is relatively high
3. The range is relatively high
4. The first order autocorrelation is relatively low

None of the computed statistics for 1972-99 is so unusual as to be an outlier in the sense of having an empirical non-exceedance probability lower than than 0.05 or greater than 0.95.

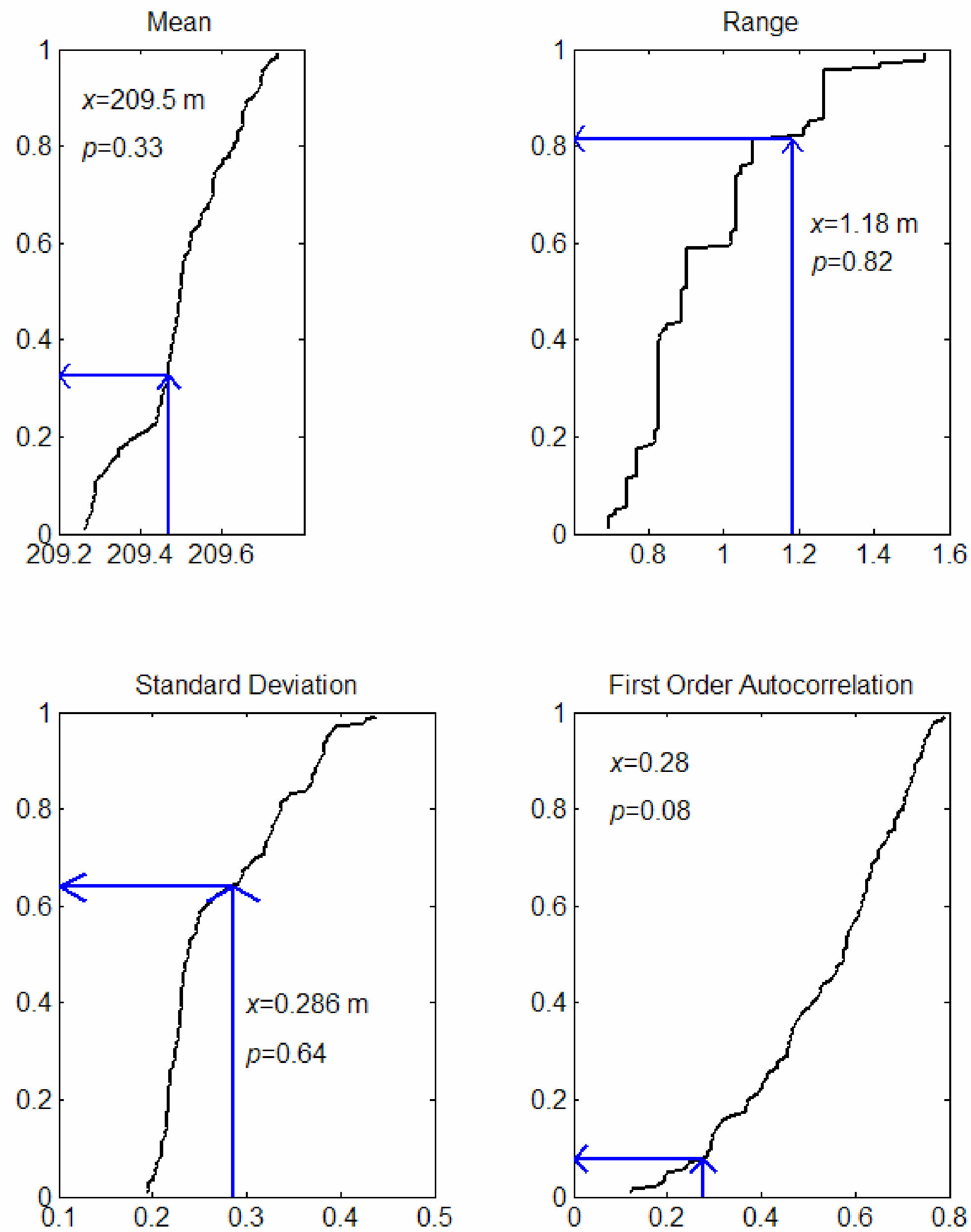



**Figure 19**. Empirical cumulative distribution functions placing post-dam reconstructed-flow statistics in long-term context. Arrow from x-axis marks the mean, range, standard deviation, and first-order autocorrelation coefficient of the reconstructed flows for 28-year period 1972-99. Arrow to y-axis gives empirical non-exceedance probability of that sample statistic based on 140 overlapping 28-year reconstructed periods, 1801-1999.

## 6 Conclusions

1. White spruce (*Picea glauca*) tree-ring chronologies from the Peace-Athabasca Delta are are significantly correlated with water-level variations of Lake Athabasca. The relationship is strong enough to allow quantitative reconstruction of annual variations in summer water level back roughly 200 years.
2. The white spruce chronologies collected in the delta in 2002 have a much stronger signal for Lake Athabasca water-level variation than any existing tree-ring chronologies from western Canada archived at the International Tree-Ring Data Bank. Reconstruction models for Lake Athabasca water-level do not appear to gain additional accuracy from tree-ring data in the remote runoff-producing areas of rivers that feed the delta.
3. The annual flow of the Peace River is amenable to reconstruction from white spruce chronologies in the delta, but reconstruction accuracy improves when delta chronologies are augmented by tree-ring series from the Canadian Rockies.
4. The annual flow of the Athabasca River is also amenable to reconstruction from tree-ring data, but the white spruce chronologies from the delta are not useful for this purpose. The useful signal appears to come from chronologies in the runoff-producing areas of the Canadian Rockies.
5. Reconstruction accuracy from models used in this study is highest for the Peace River annual flow ($R^2$=0.60), lower for Lake Athabasca water level ($R^2$=0.36), and lowest for Athabasca River annual flow ($R^2$=0.25). The regression models are all highly statistically significant, and all have skill of prediction on independent data (cross-validation), but – except for the Peace River reconstruction -- the percentage variance explained is relatively low for streamflow reconstructions. Thus the uncertainty in reconstructed time series is large. Earlier tree-ring reconstruction models that accounted for up to 80% of the variance in annual water level of Lake Athabasca used a short calibration period that in retrospect was a period of anomalously high correlation between tree-rings and water level, and used extremely complicated model structures. The high calibration accuracy was likely an artifact of overfitting the models.
6. An unusual high-amplitude wave in tree growth as indicated by mean tree-ring growth indices for the delta has occurred since about 1920. This wave is characterized by growth peaks in the 1930s and early 1960s and growth troughs in the 1940s and early 1980s. The fluctuation is larger than any other low-frequency feature in the tree-ring record back to the start of the tree-ring record in the 1680s.
7. The high amplitude wave in mean tree-ring index is damped somewhat in a reconstruction of July 11-20 mean water level for Lake Athabasca back to 1801. The damping results from the multivariate reconstruction model weighting tree-growth contrasts in the delta differently than a simple average over chronologies. In the water-level reconstruction the 1880s emerges as a period of extremely low water level.
8. Tree-ring reconstructions for the Peace River annual flow and Athabasca River annual are uncorrelated over a 183-year tree-ring record, but both reconstructions

are low in the 1880s. Low delta water levels in the 1880s may therefore have resulted from a combination of low levels on the Peace River and reduced inflow from the Athabasca River.

9. The Athabasca River reconstruction at times has the opposite sign of streamflow anomaly as the Peace River. The exceptional example is a 20-year period from about 1840 to 1860, when streamflow was near normal on the Peace River but at record low levels on the Athabasca River.
10. Spectral analysis of the streamflow and Lake Athabasca water level series does not indicate any periodicity. The spectra of the reconstructions are, however, dominated by the low frequencies. The low-frequency spectra suggest important climatic influences at multidecadal time scales, and imply that the relatively short gaged hydrologic records are inadequate to capture the natural variability of the hydrologic system.
11. Correlation analysis of smoothed time series indicates that the Lake Athabasca water-level reconstruction is much more accurate at low frequencies than at high frequencies. The smoothed reconstruction has major lows near 1890, 1945 and 1982; and major highs near 1964, 1934, and 1850. Interestingly, the major high near 1850 coincides with a major low in smoothed reconstructed annual flow of the Athabasca River.
12. Stable-isotope ratios of carbon and oxygen in rings of four sampled white spruce trees from one of the delta sites show no significant relationship with any hydrologic or climatic variables studied. The main conclusion from the stable-isotope analysis is that the tree-to-tree variability in isotope ratios is too large to be smoothed out by a sample as small as four trees. As many as 20 trees are needed for a representative sample.
13. Wilcoxon rank-sum tests indicates that samples of reconstructed Lake Athabasca water levels before and after construction of Bennett Dam are not sufficiently different to reject the null hypothesis that the samples are from the same population. The same conclusion is reached from an analysis of stable-isotope samples before and after the dam.
14. The sample mean, standard deviation, range, and first-order autocorrelaton of reconstructed Lake Athabasca water level (10-day-mean, July 11-20) for the 28-year period 1972-99 (post-dam) are not exceptional when compared with statistics computed for 140 different, overlapping, 28-year sub-samples of reconstructed water level for the period before 1968.
15. Large improvement in accuracy of the tree-ring reconstruction streamflow is probably possible with additional collections of drought-stressed tree-ring sites from the Canadian Rockies. Most of the chronologies from the International Tree-ring Data Bank have weak or nonexistent streamflow signals for the Peace and Athabasca River, yet a few chronologies have strong signals Focus on collection at site-types similar to those exhibiting a strong signal should greatly improve the reconstructions,

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**Appendix 1.** Annual values of reconstructed variables and the predictors used to generate them.

Annual values for reconstructions of water level of Lake Athabasca at Ft. Chipewyan, annual flow of Peace River at Peace River, and annual flow of Athabasca River at Athabasca are in columns labeled "Recon." Units are m above sea level and $m^3$/sec. Columns following the reconstructed values are the predictors for the reconstruction models, defined and ordered as in Table tabregsum. Note that all except two of these predictor series are principal component scores expressed as Z-scores (mean 0, standard deviation 1). The exceptions are "S.L." and "SicCk", which are standard tree-ring chronologies for Spring Lake and Sicamous Creek (see table tabcorr1).

| | Lake Athabasca Level | | | Peace River Flow | | | Athabasca River Flow | | |
|---|---|---|---|---|---|---|---|---|---|
| **YEAR** | **Recon** | **PC#1** | **PC#2** | **Recon** | **PPT/PRC** | **S.L.** | **Recon** | **Tow/WP** | **SicCk** |
| 1801 | 209.30 | -0.000 | 0.097 | 1686.0 | 0.032 | 0.920 | 407.8 | -0.651 | 0.949 |
| 1802 | 209.43 | -0.233 | -1.441 | 1673.7 | -0.230 | 0.972 | 352.6 | -1.668 | 1.059 |
| 1803 | 209.54 | 0.004 | -0.197 | 1735.5 | 0.404 | 0.911 | 390.6 | -0.324 | 1.204 |
| 1804 | 210.11 | 1.578 | 0.116 | 1948.7 | 1.733 | 0.953 | 396.3 | -0.461 | 1.110 |
| 1805 | 209.85 | 1.599 | 1.152 | 2021.1 | 1.903 | 1.050 | 411.5 | -0.263 | 1.051 |
| 1806 | 209.69 | 1.118 | -0.547 | 1821.6 | 1.096 | 0.882 | 449.8 | 0.287 | 0.921 |
| 1807 | 209.54 | -0.055 | -0.802 | 1727.4 | -0.059 | 1.031 | 471.4 | 1.117 | 1.026 |
| 1808 | 209.55 | -0.173 | 0.244 | 1615.1 | -0.111 | 0.818 | 404.7 | -0.029 | 1.188 |
| 1809 | 209.76 | 0.517 | 0.495 | 1763.2 | 0.513 | 0.935 | 445.6 | 0.604 | 1.065 |
| 1810 | 209.67 | 0.583 | 0.685 | 1751.6 | 0.236 | 0.993 | 499.6 | 1.773 | 1.016 |
| 1811 | 209.46 | 0.528 | -0.020 | 1809.0 | 0.490 | 1.035 | 424.4 | 0.493 | 1.203 |
| 1812 | 209.52 | 0.832 | -1.280 | 1844.9 | 0.395 | 1.136 | 427.6 | 0.128 | 1.051 |
| 1813 | 209.70 | 0.651 | -1.387 | 1779.5 | 0.100 | 1.090 | 425.4 | -0.238 | 0.944 |
| 1814 | 209.37 | -0.469 | 0.084 | 1655.0 | -0.593 | 1.041 | 465.1 | 0.006 | 0.697 |
| 1815 | 209.37 | -0.315 | -0.175 | 1788.6 | -0.527 | 1.293 | 383.3 | -1.951 | 0.706 |
| 1816 | 209.09 | -0.832 | -0.431 | 1738.0 | -1.080 | 1.353 | 486.2 | 1.003 | 0.863 |
| 1817 | 209.16 | -0.492 | -1.395 | 1643.3 | -0.810 | 1.081 | 387.1 | -1.184 | 0.938 |
| 1818 | 209.24 | -0.114 | -1.471 | 1696.9 | -0.619 | 1.134 | 431.3 | -0.160 | 0.921 |
| 1819 | 209.33 | -0.084 | -1.629 | 1740.0 | -0.617 | 1.221 | 494.2 | 1.095 | 0.828 |
| 1820 | 209.40 | 0.325 | -1.069 | 1800.3 | -0.147 | 1.205 | 434.5 | -0.037 | 0.937 |
| 1821 | 209.34 | -0.076 | -1.297 | 1660.5 | -0.678 | 1.077 | 478.5 | 1.016 | 0.932 |
| 1822 | 209.44 | 0.260 | -1.043 | 1799.6 | -0.193 | 1.217 | 448.2 | 0.180 | 0.897 |
| 1823 | 209.59 | 0.103 | -0.975 | 1671.4 | -0.331 | 0.997 | 457.0 | 0.532 | 0.945 |
| 1824 | 209.22 | -0.243 | 0.269 | 1725.9 | -0.043 | 1.023 | 478.2 | 0.305 | 0.690 |
| 1825 | 209.40 | -0.238 | -1.547 | 1864.4 | -0.387 | 1.406 | 443.9 | 0.216 | 0.946 |
| 1826 | 209.18 | -0.880 | -0.387 | 1732.2 | -0.481 | 1.165 | 544.0 | 2.046 | 0.740 |
| 1827 | 209.35 | -0.546 | -0.736 | 1621.9 | -0.624 | 0.983 | 513.0 | 1.462 | 0.798 |
| 1828 | 209.52 | -0.335 | -0.154 | 1638.5 | -0.720 | 1.045 | 472.0 | 0.733 | 0.889 |
| 1829 | 209.66 | -0.111 | 0.562 | 1963.6 | 0.046 | 1.480 | 519.4 | 2.121 | 0.970 |
| 1830 | 209.73 | -0.358 | 1.077 | 1809.8 | -0.126 | 1.218 | 536.8 | 2.388 | 0.917 |
| 1831 | 209.99 | 0.453 | 1.979 | 1853.9 | 1.160 | 0.929 | 413.7 | -0.190 | 1.058 |
| 1832 | 209.72 | 0.565 | 2.298 | 2011.2 | 1.146 | 1.253 | 449.7 | -0.442 | 0.671 |
| 1833 | 209.76 | 0.971 | 0.340 | 1790.8 | 1.268 | 0.769 | 418.5 | -0.631 | 0.866 |
| 1834 | 209.56 | 0.379 | -0.096 | 1787.3 | 0.524 | 0.981 | 495.0 | 1.300 | 0.892 |
| 1835 | 209.33 | -0.654 | -0.363 | 1646.3 | -0.470 | 0.987 | 487.8 | 0.801 | 0.781 |
| 1836 | 209.47 | 0.266 | -0.143 | 1721.7 | 0.543 | 0.842 | 543.0 | 1.404 | 0.528 |
| 1837 | 209.50 | -0.026 | -0.765 | 1663.1 | 0.023 | 0.876 | 444.2 | -0.580 | 0.670 |
| 1838 | 209.22 | -0.498 | -0.099 | 1799.6 | -0.430 | 1.287 | 476.5 | -0.447 | 0.446 |
| 1839 | 209.30 | -0.168 | -1.127 | 1789.1 | -0.164 | 1.187 | 456.3 | 0.660 | 0.995 |
| 1840 | 209.55 | -0.256 | -1.163 | 1705.2 | -0.263 | 1.046 | 502.8 | 0.943 | 0.704 |
| 1841 | 209.62 | -0.004 | 0.644 | 1711.7 | 0.362 | 0.875 | 432.2 | -0.721 | 0.721 |

| | Lake Athabasca Level | | | Peace River Flow | | | Athabasca River Flow | | |
|---|---|---|---|---|---|---|---|---|---|
| YEAR | Recon | PC#1 | PC#2 | Recon | PPT/PRC | S.L. | Recon | Tow/WP | SicCk |
| 1842 | 209.73 | 0.654 | 0.692 | 1611.2 | 0.578 | 0.607 | 382.5 | -1.289 | 0.940 |
| 1843 | 209.56 | -0.005 | 0.292 | 1555.3 | -0.272 | 0.744 | 361.3 | -1.508 | 1.042 |
| 1844 | 209.50 | -0.112 | 0.257 | 1756.8 | 0.300 | 0.985 | 366.2 | -1.581 | 0.976 |
| 1845 | 209.78 | 0.077 | 0.064 | 1830.0 | 0.265 | 1.144 | 407.7 | -0.065 | 1.151 |
| 1846 | 209.17 | -2.052 | 1.544 | 1633.2 | -1.555 | 1.280 | 409.9 | -0.012 | 1.151 |
| 1847 | 209.71 | -0.102 | 1.222 | 1766.1 | 0.211 | 1.030 | 296.7 | -2.243 | 1.328 |
| 1848 | 209.83 | 0.371 | 1.437 | 1801.2 | 1.031 | 0.860 | 366.9 | -0.166 | 1.456 |
| 1849 | 210.00 | 0.560 | 1.364 | 1732.4 | 0.966 | 0.739 | 389.7 | -0.432 | 1.175 |
| 1850 | 209.95 | 0.257 | 2.187 | 1791.8 | 0.589 | 0.971 | 363.1 | -0.608 | 1.336 |
| 1851 | 209.97 | 0.602 | 2.332 | 1800.1 | 0.846 | 0.912 | 334.9 | -0.957 | 1.451 |
| 1852 | 209.89 | 0.948 | 1.905 | 1759.2 | 1.148 | 0.740 | 310.9 | -2.183 | 1.230 |
| 1853 | 209.78 | 1.167 | 0.797 | 1748.0 | 1.258 | 0.685 | 381.0 | -1.309 | 0.946 |
| 1854 | 209.83 | 0.110 | -0.250 | 1646.2 | -0.273 | 0.929 | 419.3 | -0.612 | 0.866 |
| 1855 | 209.67 | 0.651 | 1.804 | 1838.1 | 0.620 | 1.056 | 398.1 | -0.714 | 1.008 |
| 1856 | 209.72 | 0.719 | -0.144 | 1738.6 | 0.228 | 0.969 | 427.5 | -0.229 | 0.929 |
| 1857 | 209.46 | 0.297 | 0.079 | 1720.7 | 0.068 | 0.980 | 433.9 | -0.198 | 0.887 |
| 1858 | 209.93 | 1.119 | -0.886 | 1829.6 | 0.605 | 1.043 | 430.6 | -0.240 | 0.900 |
| 1859 | 209.83 | 0.935 | 0.804 | 1702.3 | 0.538 | 0.804 | 323.0 | -1.881 | 1.233 |
| 1860 | 209.66 | 0.620 | 0.421 | 1687.0 | 0.266 | 0.853 | 431.3 | -0.025 | 0.968 |
| 1861 | 209.40 | 0.056 | -0.135 | 1721.5 | -0.555 | 1.165 | 377.3 | -1.273 | 0.989 |
| 1862 | 209.30 | -1.069 | -0.842 | 1607.0 | -0.952 | 1.049 | 445.9 | -0.540 | 0.669 |
| 1863 | 209.60 | -0.695 | 0.378 | 1789.5 | -0.469 | 1.278 | 399.7 | -1.786 | 0.626 |
| 1864 | 209.77 | -0.078 | 1.712 | 1607.0 | 0.139 | 0.728 | 414.0 | -1.144 | 0.727 |
| 1865 | 209.66 | -0.737 | 1.733 | 1665.2 | -0.288 | 0.972 | 454.9 | 0.071 | 0.804 |
| 1866 | 209.90 | 0.261 | 2.181 | 1796.8 | 0.712 | 0.945 | 466.5 | 0.234 | 0.763 |
| 1867 | 209.70 | -0.352 | 2.041 | 1777.4 | 0.177 | 1.063 | 499.2 | 0.136 | 0.457 |
| 1868 | 209.74 | -0.059 | 1.765 | 1894.9 | 0.126 | 1.317 | 469.5 | -0.550 | 0.469 |
| 1869 | 209.26 | -1.942 | 1.567 | 1224.3 | -1.773 | 0.513 | 435.4 | -1.382 | 0.467 |
| 1870 | 209.84 | -0.034 | 1.579 | 1716.5 | 0.106 | 0.960 | 425.5 | -1.431 | 0.533 |
| 1871 | 209.70 | 0.410 | 2.125 | 1750.0 | 0.782 | 0.829 | 450.7 | -0.453 | 0.659 |
| 1872 | 209.61 | -0.096 | 0.499 | 1549.5 | -0.004 | 0.653 | 486.7 | 0.571 | 0.711 |
| 1873 | 209.94 | 0.613 | 0.753 | 1690.1 | 0.919 | 0.667 | 487.4 | 0.543 | 0.695 |
| 1874 | 209.95 | 0.923 | 1.672 | 1854.6 | 1.053 | 0.962 | 482.9 | 0.705 | 0.788 |
| 1875 | 209.75 | 1.009 | 1.238 | 2050.9 | 1.270 | 1.297 | 476.8 | 0.782 | 0.866 |
| 1876 | 209.43 | -0.180 | -0.187 | 1799.9 | 0.390 | 1.046 | 475.6 | 0.843 | 0.897 |
| 1877 | 209.75 | 0.832 | -0.243 | 2026.7 | 0.977 | 1.334 | 426.8 | 0.388 | 1.147 |
| 1878 | 209.52 | -0.212 | 0.084 | 1723.4 | 0.148 | 0.962 | 428.0 | 0.726 | 1.253 |
| 1879 | 209.21 | -1.127 | 0.382 | 1751.9 | -0.444 | 1.194 | 509.9 | 2.226 | 1.086 |
| 1880 | 209.29 | -0.519 | -0.120 | 1735.2 | 0.127 | 0.992 | 466.0 | 1.292 | 1.131 |
| 1881 | 209.24 | -0.312 | -0.633 | 1920.5 | 0.309 | 1.315 | 507.9 | 1.732 | 0.933 |
| 1882 | 209.63 | 1.077 | -1.254 | 1897.7 | 0.657 | 1.166 | 380.6 | -0.995 | 1.057 |
| 1883 | 209.57 | 0.365 | -1.112 | 1739.1 | -0.196 | 1.095 | 408.9 | -0.290 | 1.063 |
| 1884 | 209.29 | -0.585 | -0.289 | 1671.2 | -0.665 | 1.095 | 374.6 | -0.969 | 1.116 |
| 1885 | 208.93 | -1.294 | -0.473 | 1718.1 | -1.200 | 1.348 | 392.2 | -0.199 | 1.234 |
| 1886 | 208.92 | -1.133 | -1.621 | 1424.9 | -1.516 | 0.845 | 398.8 | 0.433 | 1.396 |
| 1887 | 209.05 | -0.658 | -1.995 | 1512.4 | -1.068 | 0.891 | 442.2 | 0.453 | 1.041 |
| 1888 | 209.09 | -0.707 | -1.939 | 1589.6 | -1.166 | 1.077 | 466.3 | 1.096 | 1.061 |
| 1889 | 209.20 | -0.665 | -1.609 | 1590.0 | -1.004 | 1.030 | 378.1 | -0.786 | 1.150 |
| 1890 | 209.00 | -0.866 | -0.970 | 1592.5 | -0.919 | 1.010 | 439.9 | 0.699 | 1.145 |
| 1891 | 209.17 | -0.618 | -1.924 | 1631.1 | -0.473 | 0.957 | 367.9 | -0.571 | 1.309 |
| 1892 | 209.01 | -1.047 | -1.192 | 1563.1 | -0.643 | 0.869 | 428.2 | 0.209 | 1.074 |
| 1893 | 208.99 | -0.977 | -1.536 | 1634.9 | -0.603 | 1.003 | 440.9 | 0.510 | 1.071 |
| 1894 | 209.10 | -1.037 | -1.788 | 1675.1 | -0.465 | 1.044 | 380.1 | -1.303 | 0.956 |
| 1895 | 209.11 | -0.504 | -0.976 | 1695.9 | 0.039 | 0.938 | 451.7 | 0.500 | 0.978 |
| 1896 | 209.24 | -0.540 | -1.776 | 1637.1 | -0.126 | 0.867 | 388.8 | -0.953 | 1.003 |
| 1897 | 209.26 | -0.662 | -0.911 | 1607.1 | 0.051 | 0.754 | 408.0 | -0.017 | 1.165 |
| 1898 | 209.28 | -0.559 | -0.549 | 1679.2 | 0.026 | 0.908 | 416.0 | 0.306 | 1.209 |
| 1899 | 209.49 | -0.173 | -0.595 | 1719.4 | 0.320 | 0.903 | 447.4 | 0.105 | 0.878 |
| 1900 | 209.50 | 0.172 | 0.111 | 1905.5 | 0.698 | 1.170 | 455.4 | 1.059 | 1.139 |
| 1901 | 209.64 | 0.936 | -0.407 | 2015.4 | 1.130 | 1.266 | 497.7 | 1.582 | 0.966 |
| 1902 | 209.50 | 0.052 | -0.771 | 1757.1 | -0.082 | 1.098 | 497.4 | 1.696 | 1.008 |
| 1903 | 209.34 | -0.179 | -0.199 | 1635.8 | -0.301 | 0.916 | 449.1 | 1.221 | 1.247 |
| 1904 | 209.63 | 0.512 | -0.852 | 1705.6 | 0.119 | 0.934 | 463.8 | 1.499 | 1.220 |
| 1905 | 209.68 | 0.537 | -0.166 | 1655.7 | 0.291 | 0.782 | 412.3 | 0.166 | 1.192 |

| | Lake Athabasca Level | | | Peace River Flow | | | Athabasca River Flow | | |
|---|---|---|---|---|---|---|---|---|---|
| YEAR | Recon | PC#1 | PC#2 | Recon | PPT/PRC | S.L. | Recon | Tow/WP | SicCk |
| 1906 | 209.45 | -0.028 | 0.165 | 1707.5 | 0.146 | 0.930 | 375.7 | -1.222 | 1.020 |
| 1907 | 209.33 | -0.655 | -0.396 | 1591.9 | -0.631 | 0.924 | 439.5 | 0.344 | 1.026 |
| 1908 | 209.55 | -0.066 | -0.100 | 1698.1 | -0.085 | 0.979 | 478.1 | 1.577 | 1.128 |
| 1909 | 209.22 | -0.655 | 0.289 | 1503.1 | -0.225 | 0.624 | 464.2 | 0.762 | 0.964 |
| 1910 | 209.10 | -0.130 | -0.805 | 1661.7 | -0.051 | 0.895 | 407.4 | -0.455 | 1.019 |
| 1911 | 209.55 | 0.570 | -2.508 | 1694.3 | 0.052 | 0.931 | 457.3 | 0.814 | 1.039 |
| 1912 | 209.02 | -0.935 | -0.732 | 1480.4 | -1.214 | 0.869 | 480.9 | 1.350 | 1.027 |
| 1913 | 209.11 | -0.809 | -1.652 | 1611.8 | -1.367 | 1.181 | 460.9 | 0.874 | 1.030 |
| 1914 | 209.40 | -0.164 | -1.315 | 1750.0 | -0.976 | 1.347 | 442.5 | 0.672 | 1.114 |
| 1915 | 209.05 | -0.828 | -0.525 | 1574.6 | -1.437 | 1.126 | 431.6 | 0.302 | 1.078 |
| 1916 | 209.20 | -0.811 | -1.632 | 1734.9 | -1.372 | 1.433 | 494.6 | 1.150 | 0.844 |
| 1917 | 209.34 | -0.400 | -0.716 | 1770.0 | -0.805 | 1.337 | 474.1 | 0.816 | 0.900 |
| 1918 | 209.48 | 0.210 | -0.483 | 1772.9 | -0.455 | 1.240 | 397.5 | -0.685 | 1.023 |
| 1919 | 209.84 | 0.968 | -0.634 | 1730.1 | 0.163 | 0.971 | 339.0 | -2.276 | 0.964 |
| 1920 | 209.34 | -0.887 | 0.437 | 1520.1 | -1.219 | 0.951 | 409.5 | -0.761 | 0.897 |
| 1921 | 209.66 | 1.100 | 0.321 | 1739.8 | 0.481 | 0.897 | 368.1 | -1.862 | 0.863 |
| 1922 | 209.91 | 1.664 | -0.910 | 1566.9 | 0.547 | 0.526 | 350.6 | -2.055 | 0.943 |
| 1923 | 209.81 | 0.797 | -0.276 | 1644.4 | 0.138 | 0.804 | 421.0 | -0.539 | 0.877 |
| 1924 | 209.59 | -0.051 | 0.533 | 1649.4 | -0.024 | 0.862 | 414.2 | -0.671 | 0.888 |
| 1925 | 209.79 | 0.932 | 0.561 | 1611.8 | 0.497 | 0.632 | 413.8 | -0.149 | 1.071 |
| 1926 | 209.77 | 0.319 | 0.161 | 1598.0 | 0.168 | 0.701 | 432.2 | 0.103 | 1.004 |
| 1927 | 209.67 | 0.879 | 1.075 | 1788.6 | 0.781 | 0.908 | 477.3 | 0.803 | 0.869 |
| 1928 | 209.24 | -1.049 | -0.486 | 1493.7 | -1.115 | 0.867 | 461.1 | 0.548 | 0.916 |
| 1929 | 209.20 | -0.794 | -0.045 | 1480.1 | -1.050 | 0.820 | 401.3 | -1.090 | 0.852 |
| 1930 | 209.78 | 0.683 | -0.737 | 1580.4 | 0.176 | 0.663 | 429.6 | -0.173 | 0.931 |
| 1931 | 209.73 | 0.614 | 0.542 | 1552.5 | 0.584 | 0.486 | 385.3 | -1.130 | 0.971 |
| 1932 | 210.10 | 1.750 | 0.319 | 1835.7 | 1.527 | 0.784 | 424.0 | -0.160 | 0.982 |
| 1933 | 209.82 | 1.018 | 0.816 | 1817.1 | 0.831 | 0.951 | 345.2 | -1.686 | 1.115 |
| 1934 | 210.04 | 1.696 | 0.261 | 1947.8 | 1.312 | 1.075 | 377.0 | -1.043 | 1.071 |
| 1935 | 210.04 | 2.371 | 0.520 | 2163.6 | 2.092 | 1.284 | 409.5 | -0.228 | 1.080 |
| 1936 | 210.03 | 1.635 | -0.628 | 1803.2 | 1.210 | 0.811 | 327.6 | -1.371 | 1.370 |
| 1937 | 209.78 | 0.515 | 0.575 | 1775.0 | 0.299 | 1.022 | 396.3 | -0.177 | 1.207 |
| 1938 | 209.39 | -0.910 | 0.799 | 1616.0 | -0.615 | 0.968 | 392.4 | 0.207 | 1.372 |
| 1939 | 209.05 | -1.996 | 0.718 | 1468.3 | -1.780 | 1.011 | 386.3 | -0.489 | 1.183 |
| 1940 | 209.07 | -1.562 | 0.343 | 1761.5 | -1.124 | 1.414 | 323.0 | -1.361 | 1.412 |
| 1941 | 209.27 | -1.058 | -0.286 | 1437.2 | -0.694 | 0.628 | 335.2 | -0.986 | 1.439 |
| 1942 | 209.26 | -1.564 | 0.205 | 1603.1 | -1.257 | 1.131 | 426.1 | 0.728 | 1.270 |
| 1943 | 208.87 | -2.411 | 0.954 | 1561.2 | -1.862 | 1.224 | 441.7 | 0.817 | 1.170 |
| 1944 | 209.17 | -1.840 | -0.115 | 1561.3 | -1.773 | 1.198 | 385.8 | 0.312 | 1.463 |
| 1945 | 208.83 | -2.743 | 0.819 | 1444.5 | -2.525 | 1.182 | 414.1 | 0.466 | 1.280 |
| 1946 | 208.96 | -2.031 | 0.196 | 1312.9 | -2.089 | 0.786 | 474.8 | 1.244 | 1.041 |
| 1947 | 209.36 | -0.929 | -0.214 | 1528.6 | -1.421 | 1.028 | 487.6 | 1.870 | 1.149 |
| 1948 | 209.45 | -0.549 | 0.521 | 1608.6 | -0.937 | 1.048 | 445.9 | 1.142 | 1.247 |
| 1949 | 209.73 | 0.055 | 0.515 | 1654.7 | -1.353 | 1.264 | 354.3 | -1.403 | 1.136 |
| 1950 | 209.27 | -1.368 | 1.290 | 1690.8 | -1.542 | 1.393 | 434.0 | 0.187 | 1.018 |
| 1951 | 209.53 | -0.770 | 0.699 | 1585.9 | -0.951 | 1.006 | 480.7 | 0.776 | 0.831 |
| 1952 | 209.41 | -1.276 | 1.381 | 1567.4 | -1.245 | 1.055 | 430.0 | -0.214 | 0.914 |
| 1953 | 209.30 | -1.322 | 1.463 | 1450.2 | -0.944 | 0.728 | 486.9 | 1.412 | 0.998 |
| 1954 | 209.38 | -1.172 | 0.799 | 1708.9 | -0.951 | 1.256 | 515.7 | 1.538 | 0.801 |
| 1955 | 209.43 | -0.774 | 1.075 | 1749.0 | -0.603 | 1.235 | 479.7 | 0.654 | 0.798 |
| 1956 | 209.86 | 0.720 | 0.757 | 1711.7 | 0.450 | 0.849 | 450.5 | -0.244 | 0.732 |
| 1957 | 209.78 | 0.480 | 1.018 | 1760.8 | 0.521 | 0.928 | 409.2 | -0.831 | 0.875 |
| 1958 | 210.02 | 1.550 | 0.903 | 2087.1 | 1.476 | 1.310 | 386.4 | -0.890 | 1.045 |
| 1959 | 210.05 | 2.230 | 0.614 | 1965.0 | 2.436 | 0.779 | 446.7 | -0.349 | 0.728 |
| 1960 | 210.02 | 1.892 | -0.339 | 2075.4 | 1.819 | 1.185 | 396.1 | -1.134 | 0.880 |
| 1961 | 209.65 | 0.794 | 0.070 | 1814.9 | 0.956 | 0.910 | 364.3 | -2.098 | 0.814 |
| 1962 | 209.87 | 1.367 | -0.476 | 1855.8 | 1.221 | 0.915 | 482.3 | 0.459 | 0.709 |
| 1963 | 210.25 | 2.668 | -0.012 | 2196.7 | 2.694 | 1.174 | 402.7 | -0.600 | 1.009 |
| 1964 | 210.16 | 2.186 | 0.250 | 2263.5 | 2.721 | 1.302 | 465.4 | 0.718 | 0.939 |
| 1965 | 210.37 | 3.193 | 0.439 | 2301.7 | 3.463 | 1.161 | 435.7 | 0.335 | 1.055 |
| 1966 | 210.07 | 2.163 | 0.141 | 2217.7 | 2.479 | 1.280 | 458.2 | 0.827 | 1.036 |
| 1967 | 209.77 | 1.292 | -0.077 | 1919.2 | 1.947 | 0.830 | 391.2 | -0.624 | 1.096 |
| 1968 | 209.91 | 1.550 | -0.534 | 1799.6 | 1.723 | 0.653 | 412.2 | -0.815 | 0.856 |
| 1969 | 209.62 | 0.919 | -0.051 | 1762.1 | 0.846 | 0.835 | 424.6 | -0.274 | 0.938 |
| 1970 | 209.28 | -0.583 | -0.919 | 1474.0 | -0.766 | 0.724 | 429.8 | -0.394 | 0.853 |
| 1971 | 209.34 | -0.253 | -0.575 | 1489.2 | -0.434 | 0.657 | 464.9 | -0.091 | 0.665 |

| | Lake Athabasca Level | | | Peace River Flow | | | Athabasca River Flow | | |
|---|---|---|---|---|---|---|---|---|---|
| **YEAR** | **Recon** | **PC#1** | **PC#2** | **Recon** | **PPT/PRC** | **S.L.** | **Recon** | **Tow/WP** | **SicCk** |
| 1972 | 209.58 | -0.284 | -0.701 | 1581.6 | -0.373 | 0.827 | 461.2 | -0.430 | 0.579 |
| 1973 | 209.23 | -0.616 | 0.865 | 1552.6 | -0.383 | 0.771 | 480.5 | 0.530 | 0.748 |
| 1974 | 209.92 | 0.707 | -0.834 | 1656.6 | 0.474 | 0.730 | 449.5 | -0.359 | 0.701 |
| 1975 | 209.77 | 1.090 | 1.379 | 1863.5 | 1.118 | 0.961 | 395.4 | -1.422 | 0.787 |
| 1976 | 209.77 | 0.883 | -0.210 | 1853.2 | 0.809 | 1.031 | 417.5 | -0.640 | 0.871 |
| 1977 | 209.79 | 0.117 | 0.130 | 1904.0 | -0.087 | 1.398 | 375.2 | -1.155 | 1.047 |
| 1978 | 209.47 | -0.435 | 1.544 | 1836.7 | 0.148 | 1.192 | 478.8 | 1.048 | 0.940 |
| 1979 | 209.69 | -0.690 | 0.438 | 1672.8 | 0.066 | 0.883 | 452.0 | 0.270 | 0.897 |
| 1980 | 208.95 | -2.448 | 2.250 | 1578.8 | -1.401 | 1.124 | 474.3 | 0.780 | 0.886 |
| 1981 | 209.22 | -1.803 | 0.462 | 1778.5 | -1.309 | 1.503 | 476.4 | 1.402 | 1.082 |
| 1982 | 208.73 | -2.894 | 1.087 | 1433.6 | -2.148 | 1.049 | 514.7 | 1.439 | 0.775 |
| 1983 | 209.18 | -1.514 | -0.219 | 1659.1 | -1.122 | 1.205 | 434.0 | -0.243 | 0.870 |
| 1984 | 209.30 | -0.966 | 0.376 | NaN | NaN | NaN | 420.2 | -0.166 | 1.012 |
| 1985 | 209.22 | -0.779 | 0.242 | NaN | NaN | NaN | 355.5 | -1.604 | 1.057 |
| 1986 | 209.48 | 0.030 | -0.634 | NaN | NaN | NaN | 424.1 | -0.068 | 1.013 |
| 1987 | 209.49 | -0.298 | -0.274 | NaN | NaN | NaN | 413.1 | 0.510 | 1.303 |
| 1988 | 209.57 | 0.122 | 0.294 | NaN | NaN | NaN | 399.8 | 0.284 | 1.336 |
| 1989 | 209.71 | 0.790 | 0.113 | NaN | NaN | NaN | 387.0 | -0.058 | 1.326 |
| 1990 | 209.36 | -0.415 | -0.111 | NaN | NaN | NaN | 479.1 | 1.708 | 1.165 |
| 1991 | 209.53 | 0.427 | -0.354 | NaN | NaN | NaN | 515.5 | 1.669 | 0.848 |
| 1992 | 209.38 | 0.218 | -0.643 | NaN | NaN | NaN | 380.7 | -0.297 | 1.296 |
| 1993 | 209.69 | 0.916 | -1.269 | NaN | NaN | NaN | NaN | NaN | NaN |
| 1994 | 209.86 | 1.146 | -0.405 | NaN | NaN | NaN | NaN | NaN | NaN |
| 1995 | 209.25 | -0.303 | 0.283 | NaN | NaN | NaN | NaN | NaN | NaN |
| 1996 | 209.46 | 0.899 | -1.228 | NaN | NaN | NaN | NaN | NaN | NaN |
| 1997 | 209.65 | 1.285 | -1.914 | NaN | NaN | NaN | NaN | NaN | NaN |
| 1998 | 209.74 | 0.495 | -1.352 | NaN | NaN | NaN | NaN | NaN | NaN |
| 1999 | 209.12 | -0.767 | 0.602 | NaN | NaN | NaN | NaN | NaN | NaN |
| 2000 | NaN | -0.848 | -1.264 | NaN | NaN | NaN | NaN | NaN | NaN |

**Appendix 2.** Observed annual time series of water level and streamflow .

Water level series is water level of Lake Athabasca at Ft. Chipewyan in units of meters above sea level averaged for the ten days July 11-20. Streamflow series are totals in $m^3$/sec for water year (Oct 1-Sept 30) of Peace River at Peace River and at Peace Point, and of Athabasca River at Athabasca. Data were computed from spreadsheets of daily data, adjusted as needed as described in report. Water level values for 1945, 1946 and 1954 from Stockton and Fritts (1973). NaN is missing value code, indicating insufficient data to compute the series.

| | | Peace R. | | Athabasca R. |
|---|---|---|---|---|
| **YEAR** | **Water Level** | **at Peace River** | **at Peace Point** | **at Athabasca** |
| 1915 | NaN | NaN | NaN | 476.3 |
| 1916 | NaN | 1647.1 | NaN | 374.4 |
| 1917 | NaN | 1376.6 | NaN | 419.4 |
| 1918 | NaN | 1768.4 | NaN | 370.8 |
| 1919 | NaN | 1734.6 | NaN | 293.5 |
| 1920 | NaN | 2146.0 | NaN | 511.4 |
| 1921 | NaN | 2040.1 | NaN | 434.7 |
| 1922 | NaN | 1579.4 | NaN | 316.5 |
| 1923 | NaN | 1765.1 | NaN | 374.1 |
| 1924 | NaN | 1474.3 | NaN | 414.7 |
| 1925 | NaN | 1453.4 | NaN | 481.1 |
| 1926 | NaN | 1416.6 | NaN | 391.2 |
| 1927 | NaN | 1744.8 | NaN | 509.6 |
| 1928 | NaN | 1598.6 | NaN | 471.9 |
| 1929 | NaN | 1321.0 | NaN | 344.7 |
| 1930 | NaN | 1550.3 | NaN | 420.4 |
| 1931 | NaN | 1517.1 | NaN | NaN |
| 1932 | NaN | NaN | NaN | NaN |
| 1933 | NaN | NaN | NaN | NaN |
| 1934 | 209.85 | NaN | NaN | NaN |
| 1935 | 211.33 | NaN | NaN | NaN |
| 1936 | 210.92 | NaN | NaN | NaN |
| 1937 | 209.65 | NaN | NaN | NaN |
| 1938 | 208.90 | NaN | NaN | NaN |
| 1939 | 209.16 | NaN | NaN | NaN |
| 1940 | 209.54 | NaN | NaN | NaN |
| 1941 | 209.16 | NaN | NaN | NaN |
| 1942 | 209.79 | NaN | NaN | NaN |
| 1943 | 209.65 | NaN | NaN | NaN |
| 1944 | 209.03 | NaN | NaN | NaN |
| 1945 | 208.47 | NaN | NaN | NaN |
| 1946 | 208.75 | NaN | NaN | NaN |
| 1947 | 209.65 | NaN | NaN | NaN |
| 1948 | 210.12 | NaN | NaN | NaN |
| 1949 | 209.17 | NaN | NaN | NaN |

**Appendix 2** (continued)

| YEAR | Water Level | Peace R. at Peace River | Peace R. at Peace Point | Athabasca R. at Athabasca |
|---|---|---|---|---|
| 1950 | 209.29 | NaN | NaN | NaN |
| 1951 | 209.75 | NaN | NaN | NaN |
| 1952 | 209.35 | NaN | NaN | 403.1 |
| 1953 | 209.05 | NaN | NaN | 455.3 |
| 1954 | 210.49 | NaN | NaN | 703.8 |
| 1955 | 209.73 | NaN | NaN | 469.0 |
| 1956 | 209.39 | NaN | NaN | 405.2 |
| 1957 | 209.36 | NaN | NaN | 354.8 |
| 1958 | 209.84 | NaN | NaN | 421.7 |
| 1959 | 209.65 | 1783.5 | NaN | 327.8 |
| 1960 | 210.45 | 2061.5 | 2302.1 | 380.3 |
| 1961 | 209.84 | 1642.7 | 1905.5 | 311.2 |
| 1962 | 210.56 | 2014.8 | 2352.2 | 453.1 |
| 1963 | 210.09 | 2183.3 | 2365.8 | 417.9 |
| 1964 | 210.40 | 2577.2 | 2725.4 | 405.2 |
| 1965 | 210.52 | 2244.1 | 2403.5 | 680.3 |
| 1966 | 209.89 | 2146.2 | 2290.3 | 489.1 |
| 1967 | 210.46 | 2056.4 | 2136.7 | 400.0 |
| 1968 | 208.73 | 1024.9 | 1191.7 | 327.1 |
| 1969 | 208.65 | 1024.0 | 1162.2 | 366.6 |
| 1970 | 208.67 | 1276.3 | 1467.4 | 357.6 |
| 1971 | 209.07 | 1595.2 | 1704.7 | 559.0 |
| 1972 | 209.88 | 2141.8 | 2210.3 | 533.7 |
| 1973 | 209.58 | 2105.9 | 2502.1 | 442.9 |
| 1974 | 210.09 | 2056.9 | 2468.9 | 570.5 |
| 1975 | 209.26 | 1733.3 | 2124.4 | 377.2 |
| 1976 | 209.40 | 2217.9 | 2503.2 | 417.2 |
| 1977 | 209.78 | 2110.3 | 2323.2 | 546.1 |
| 1978 | 209.44 | 1745.8 | 2039.8 | 532.1 |
| 1979 | 209.98 | 1954.5 | 2275.9 | 494.8 |
| 1980 | 208.79 | 1440.0 | 1529.7 | 476.3 |
| 1981 | 208.94 | 1693.8 | 1839.3 | 385.8 |
| 1982 | 208.97 | 1991.2 | 2077.0 | 477.3 |
| 1983 | 208.82 | 1835.7 | 2008.7 | 398.9 |
| 1984 | 209.08 | 1858.8 | 2035.4 | 373.9 |
| 1985 | 209.44 | 2013.8 | 2112.5 | 402.3 |
| 1986 | 209.46 | 1799.8 | 2109.7 | 491.1 |
| 1987 | 209.17 | 2126.6 | 2359.2 | 362.5 |
| 1988 | 209.18 | 1972.6 | 2350.4 | 297.4 |
| 1989 | 209.48 | 1855.3 | 2164.8 | 472.2 |
| 1990 | 209.75 | 1921.2 | 2139.7 | 495.3 |
| 1991 | 209.68 | 1707.5 | 1929.9 | 482.3 |
| 1992 | 209.36 | 1960.8 | 2137.8 | 310.1 |
| 1993 | 208.88 | 1785.4 | 1882.9 | 312.8 |
| 1994 | 209.47 | 1924.5 | 1995.3 | 423.8 |
| 1995 | 208.74 | 1561.6 | 1527.4 | 386.2 |
| 1996 | 210.02 | 2782.9 | 3227.1 | 498.9 |
| 1997 | 210.39 | 2279.6 | 2909.7 | 601.8 |
| 1998 | 209.50 | 1846.4 | 2008.5 | 377.6 |
| 1999 | 208.64 | 1910.7 | 1887.5 | 414.1 |
| 2000 | NaN | 1791.7 | 1883.7 | 342.3 |

**Appendix 3.** Seasonal precipitation components computed from daily data at Ft. Chipewyan..

Year=water year (e.g., water year 1968 is Oct 1, 1967 to Sept 30, 1968)
Water Year=total precipitation (mm) for water year
Summer=total precipitation (mm) for period June 1 to Sept 30
Percentage=percentage of water-year precipitation falling in summer; compute as 100 times the ratio of column 3 to column 2

| YEAR | Water Year | Summer | Percentage |
|---|---|---|---|
| 1968 | NaN | 192.70 | NaN |
| 1969 | 298.90 | 134.60 | 45.03 |
| 1970 | 359.90 | 175.40 | 48.74 |
| 1971 | 437.40 | 261.20 | 59.72 |
| 1972 | 415.10 | 208.10 | 50.13 |
| 1973 | 410.80 | 267.20 | 65.04 |
| 1974 | 483.30 | 233.10 | 48.23 |
| 1975 | 344.90 | 193.40 | 56.07 |
| 1976 | 426.40 | 207.80 | 48.73 |
| 1977 | 411.60 | 247.60 | 60.16 |
| 1978 | 409.50 | 257.00 | 62.76 |
| 1979 | 361.10 | 182.80 | 50.62 |
| 1980 | NaN | 115.40 | NaN |
| 1981 | NaN | 160.20 | NaN |
| 1982 | NaN | 137.80 | NaN |
| 1983 | 369.10 | 173.90 | 47.11 |
| 1984 | 360.70 | 208.30 | 57.75 |
| 1985 | 349.70 | 132.60 | 37.92 |
| 1986 | 488.50 | 269.40 | 55.15 |
| 1987 | 397.20 | 220.00 | 55.39 |
| 1988 | 432.20 | 204.60 | 47.34 |
| 1989 | 363.10 | 178.60 | 49.19 |
| 1990 | 326.60 | 135.80 | 41.58 |
| 1991 | 474.20 | 237.40 | 50.06 |
| 1992 | NaN | NaN | NaN |
| 1993 | 352.30 | 217.20 | 61.65 |

**Appendix 5.** Key to tree species codes

The species of tree-ring chronologies in the International Tree-Ring Data Bank are identified by four-letter codes as defined here.

| Code | Latin name and authority | Common Name |
|---|---|---|
| ABAM | *Abies amabilis* Dougl. ex Forbes | Pacific silver fir |
| ABLA | *Abies lasiocarpa* (Hook.) Nutt. | subalpine fir |
| PCEN | *Picea engelmannii* Parry ex Engelm. | Engelmann spruce |
| PCGL | *Picea glauca* (Moench) Voss | white spruce |
| PCMA | Picea mariana (Mill.) Britt., Sterns & Poggenb. | black spruce |
| PIBN | *Pinus banksiana* Lamb. | jack pine |
| PIFL | *Pinus flexilis* James | limber pine |
| PSME | *Pseudotsuga menziesii* (Mirb.) Franco | Douglas-fir |
| PIPO | *Pinus ponderosa* Dougl. ex Laws. | ponderosa pine |

**Appendix 6.** Gaussian filter weights used in smoothing time series

Listed below are the smoothing weights for 10-year, 25-year, and 50-year Gaussian filters computed following Mitchell et al. (1966). The *n*-year filters are designed to have approximate amplitude of frequency response of 0.5 at wavelength *n* years. Much shorter wavelengths are filtered out and longer wavelengths passed (low-pass) by the filters. Weights for each filter sum to 1.0, but not exactly so in the listing below because of rounding.

| | 10-year | 25-year | 50-year |
|---|---|---|---|
| 1 | 0.013519569 | 0.005437408 | 0.002725049 |
| 2 | 0.047662179 | 0.009398052 | 0.003608479 |
| 3 | 0.117230044 | 0.015334457 | 0.004709993 |
| 4 | 0.201167560 | 0.023620203 | 0.006059859 |
| 5 | 0.240841296 | 0.034346579 | 0.007685124 |
| 6 | 0.201167560 | 0.047148510 | 0.009606947 |
| 7 | 0.117230044 | 0.061099423 | 0.011837666 |
| 8 | 0.047662179 | 0.074746502 | 0.014377816 |
| 9 | 0.013519569 | 0.086323547 | 0.017213371 |
| 10 | NaN | 0.094113586 | 0.020313516 |
| 11 | NaN | 0.096863466 | 0.023629276 |
| 12 | NaN | 0.094113586 | 0.027093300 |
| 13 | NaN | 0.086323547 | 0.030621013 |
| 14 | NaN | 0.074746502 | 0.034113270 |
| 15 | NaN | 0.061099423 | 0.037460478 |
| 16 | NaN | 0.047148510 | 0.040548000 |
| 17 | NaN | 0.034346579 | 0.043262511 |
| 18 | NaN | 0.023620203 | 0.045498823 |
| 19 | NaN | 0.015334457 | 0.047166621 |
| 20 | NaN | 0.009398052 | 0.048196503 |
| 21 | NaN | 0.005437408 | 0.048544770 |
| 22 | NaN | NaN | 0.048196503 |
| 23 | NaN | NaN | 0.047166621 |
| 24 | NaN | NaN | 0.045498823 |
| 25 | NaN | NaN | 0.043262511 |
| 26 | NaN | NaN | 0.040548000 |
| 27 | NaN | NaN | 0.037460478 |
| 28 | NaN | NaN | 0.034113270 |
| 29 | NaN | NaN | 0.030621013 |
| 30 | NaN | NaN | 0.027093300 |
| 31 | NaN | NaN | 0.023629276 |
| 32 | NaN | NaN | 0.020313516 |
| 33 | NaN | NaN | 0.017213371 |
| 34 | NaN | NaN | 0.014377816 |
| 35 | NaN | NaN | 0.011837666 |
| 36 | NaN | NaN | 0.009606947 |
| 37 | NaN | NaN | 0.007685124 |
| 38 | NaN | NaN | 0.006059859 |
| 39 | NaN | NaN | 0.004709993 |
| 40 | NaN | NaN | 0.003608479 |
| 41 | NaN | NaN | 0.002725049 |

**Appendix 7.** Comparison of two Lake Athabasca water level reconstructions

The 10-day-mean (July 11-20) Lake Athabasca water level reconstructed in this study is plotted below with the corresponding reconstruction published by Stockton and Fritts (1973) and listed in Appendix II of Stockton and Fritts (1971). The Stockton and Fritts (1971) data are listed in units of feet with 3 digits to the right of the decimal point. These data entered into a spreadsheet after rounding to the nearest hundredths of feet, and then converted to meters above msl.

Correlation coefficients between the two series for the period 1935-67 (calibration period of the Stockton and Fritts model) and 1810-1934 are as follows:
1935-67: $r = 0.71$
1810-1934: $r = -0.10$